

Very long baselines with a superbeam

Milind Diwan

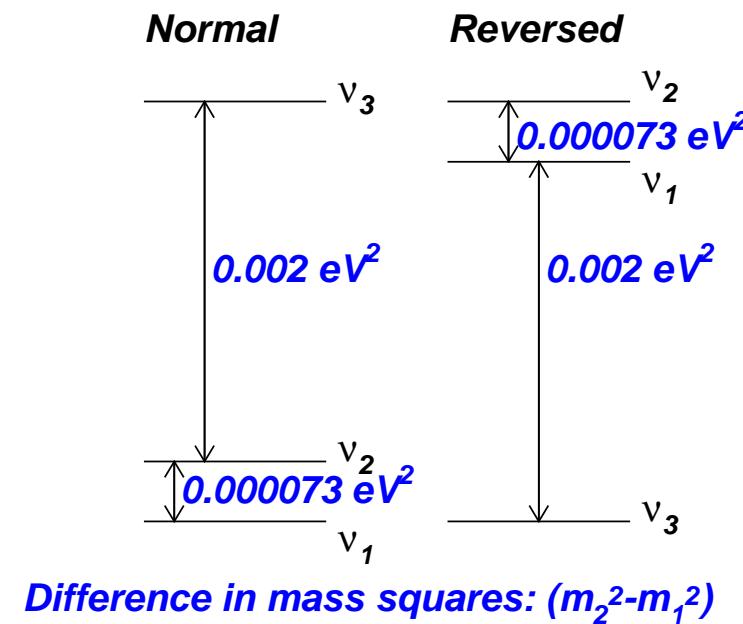
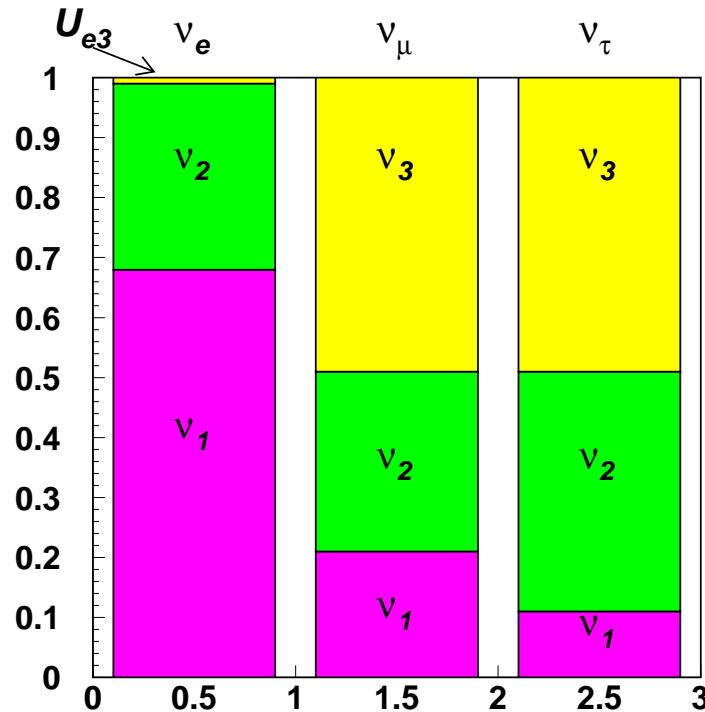
FOR BNL Neutrino Working Group.

December 12, 2003

University of Maryland

Wide Band Conventional Beam from BNL to the
Homestake Laboratory.

Big Picture



Very long baselines with a superbeam

Neutrino Physics so far

- Evidence for Neutrino flavor change
 - Atmospheric neutrinos: SuperK
 - Solar: SNO, All previous radio-chemical measurements.
 - KamLAND: Confirm the solar LMA solution.
 - Limits on parameters from many accelerator and reactor exp.
 - LSND: To be addressed by mini-boone.
- Direct Neutrino mass
 - Oscillations: Neutrinos definitely have mass.
 - Tritium beta-decay: < 2.8 eV.
 - Double beta decay: mass < 0.3 eV if Majorana.
 - Astrophysics: Large Scale Structure < 1 eV.
- Number of Neutrinos
 - Z width: 2.981 ± 0.008 active types
 - Limits on sterile neutrinos from solar, atmospheric results.
 - Big Bang Nucleosynthesis: 3 active neutrinos.

Neutrino Physics: Oscillations

Assume a 2×2 neutrino mixing matrix.

$$\begin{pmatrix} \nu_a \\ \nu_b \end{pmatrix} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \quad (1)$$

$$\begin{aligned} \nu_a(t) &= \cos(\theta)\nu_1(t) + \sin(\theta)\nu_2(t) \\ P(\nu_a \rightarrow \nu_b) &= |<\nu_b|\nu_a(t)>|^2 \\ &= \sin^2(\theta)\cos^2(\theta)|e^{-iE_2t} - e^{-iE_1t}|^2 \end{aligned} \quad (2)$$

Sufficient to understand most of the physics:

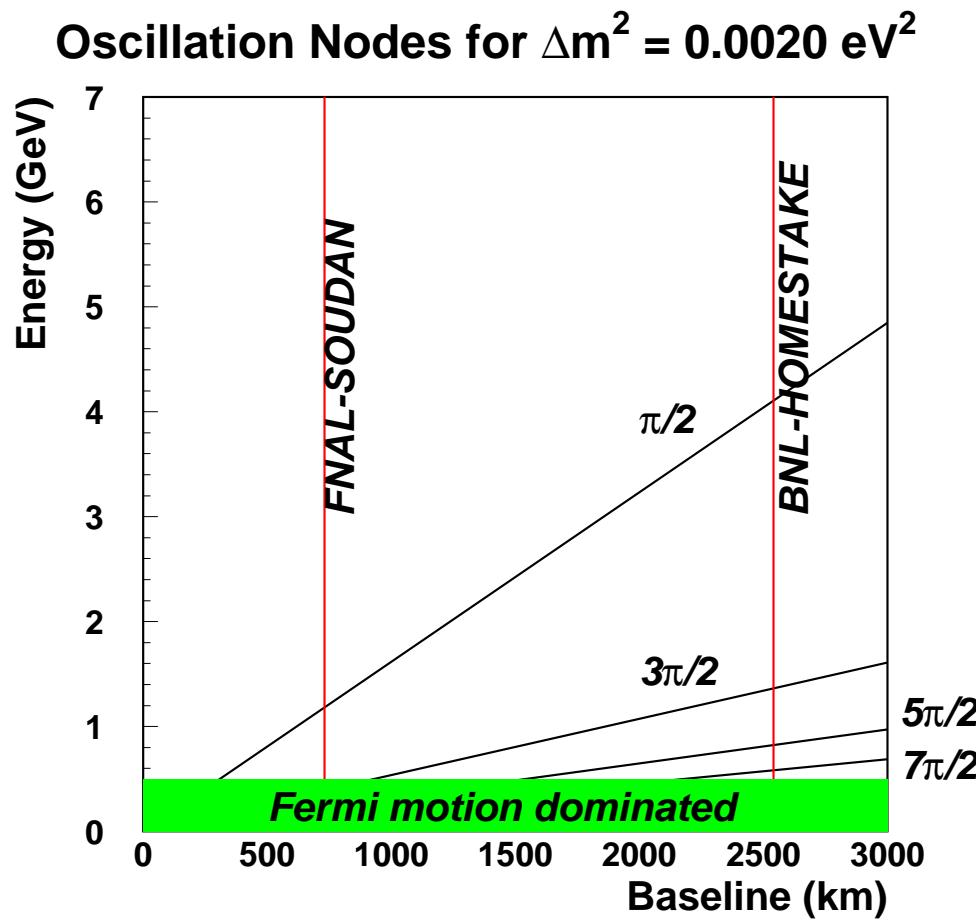
$$P(\nu_a \rightarrow \nu_b) = \sin^2 2\theta \sin^2 \frac{1.27((m_2^2 - m_1^2)/eV^2)(L/km)}{(E/GeV)}$$

$$P(\nu_a \rightarrow \nu_a) = 1 - \sin^2 2\theta \sin^2 \frac{1.27(\Delta m^2/eV^2)(L/km)}{(E/GeV)}$$

Oscillation nodes at $\pi/2, 3\pi/2, 5\pi/2, \dots (\pi/2)$:
 $\Delta m^2 = 0.002eV^2$, $E = 1GeV$, $L = 618km$.

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Matter Effect



- Large effects: Multiple oscillation nodes.
- Low cross section at low energies
- Fermi motion limits resolution at low energies: wide band beam ($0.5 \rightarrow 8 \text{ GeV}$).
- $\Delta m^2 \approx 0.002 \text{ eV}^2$: Baseline $> 2000 \text{ km}$.

Neutrino Physics: 3×3 Formulation

Bill Marciano, hep-ph/0108181

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \quad (3)$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \quad (4)$$

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Neutrino Physics: the difficult stuff

$$\begin{aligned}
 P(\nu_\mu \rightarrow \nu_e) = & 4(s_2^2 s_3^2 c_3^2 + J_{CP} \sin \Delta_{21}) \sin^2 \frac{\Delta_{31}}{2} \\
 & + 2(s_1 s_2 s_3 c_1 c_2 c_3^2 \cos \delta - s_1^2 s_2^2 s_3^2 c_3^2) \sin \Delta_{31} \sin \Delta_{21} \\
 & + 4(s_1^2 c_1^2 c_2^2 c_3^2 + s_1^4 s_2^2 s_3^2 c_3^2 - 2s_1^3 s_2 s_3 c_1 c_2 c_3^2 \cos \delta) \\
 & \quad - J_{CP} \sin \Delta_{31}) \sin^2 \frac{\Delta_{21}}{2} \\
 & + 8(s_1 s_2 s_3 c_1 c_2 c_3^2 \cos \delta - s_1^2 s_2^2 s_3^2 c_3^2) \sin^2 \frac{\Delta_{31}}{2} \sin^2 \frac{\Delta_{21}}{2}
 \end{aligned} \tag{5}$$

No matter effects in above formula

$$\Delta_{31} \equiv \Delta m_{31}^2 L / 2E_\nu$$

$$\Delta_{21} \equiv \Delta m_{21}^2 L / 2E_\nu$$

$$J_{CP} \equiv s_1 s_2 s_3 c_1 c_2 c_3^2 \sin \delta \quad (6)$$

$$A \equiv \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \quad (7)$$

To leading order in Δ_{21} (assumed to be small), one finds

$$\begin{aligned} P(\nu_\mu \rightarrow \nu_e) &\simeq 4s_2^2 s_3^2 c_3^2 \sin^2 \frac{\Delta_{31}}{2} + \mathcal{O}(\Delta_{21}) \\ A &\simeq \frac{J_{CP} \sin \Delta_{21}}{s_2^2 s_3^2 c_3^2} \simeq \frac{2s_1 c_1 c_2 \sin \delta}{s_2 s_3} \left(\frac{\Delta m_{21}^2}{\Delta m_{31}^2} \right) \frac{\Delta m_{31}^2 L}{4E_\nu} + \mathcal{O}(\Delta_{21}^2) \end{aligned}$$

$\nu_\mu \rightarrow \nu_e$ with matter effect

Approximate formula (Lindener, Huber et al.)

$$\begin{aligned}
 P(\nu_\mu \rightarrow \nu_e) \approx & \sin^2 \theta_{23} \frac{\sin^2 2\theta_{13}}{(\hat{A} - 1)^2} \sin^2((\hat{A} - 1)\Delta) \\
 & + \alpha \frac{8J_{CP}}{\hat{A}(1 - \hat{A})} \sin(\Delta) \sin(\hat{A}\Delta) \sin((1 - \hat{A})\Delta) \\
 & + \alpha \frac{8I_{CP}}{\hat{A}(1 - \hat{A})} \sin(\Delta) \cos(\hat{A}\Delta) \sin((1 - \hat{A})\Delta) \\
 & + \alpha^2 \frac{\cos^2 \theta_{23} \sin^2 2\theta_{12}}{\hat{A}^2} \sin^2(\hat{A}\Delta)
 \end{aligned} \tag{8}$$

$$J_{CP} = 1/8 \sin \delta_{CP} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23}$$

$$I_{CP} = 1/8 \cos \delta_{CP} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23}$$

$$\alpha = \Delta m_{21}^2 / \Delta m_{31}^2, \Delta = \Delta m_{31}^2 L / 4E$$

$$\hat{A} = 2VE / \Delta m_{31}^2$$

Comments about matter effect

$V = \sqrt{2}G_F n_e$. n_e is the density of electrons in the Earth.

$$\hat{A} \approx 7.6 \times 10^{-5} \times (D/gm/cm^3) \times (E_\nu/GeV)/(\Delta m_{31}^2/eV^2),$$

Also recall $\Delta m_{31}^2 = \Delta m_{32}^2 + \Delta m_{21}^2$.

- This is a very approximate equation, not applicable below the first maximum.
- First term has the effect of $\sin^2 2\theta_{13}$ and matter.
- Second and third terms have effects of CP.
- Term with J_{CP} changes sign for $(Anti - \nu_\mu) \rightarrow (Anti - \nu_e)$
- Last term is almost independent of Δm_{31}^2 and is purely dominated by the solar Δm_{21}^2

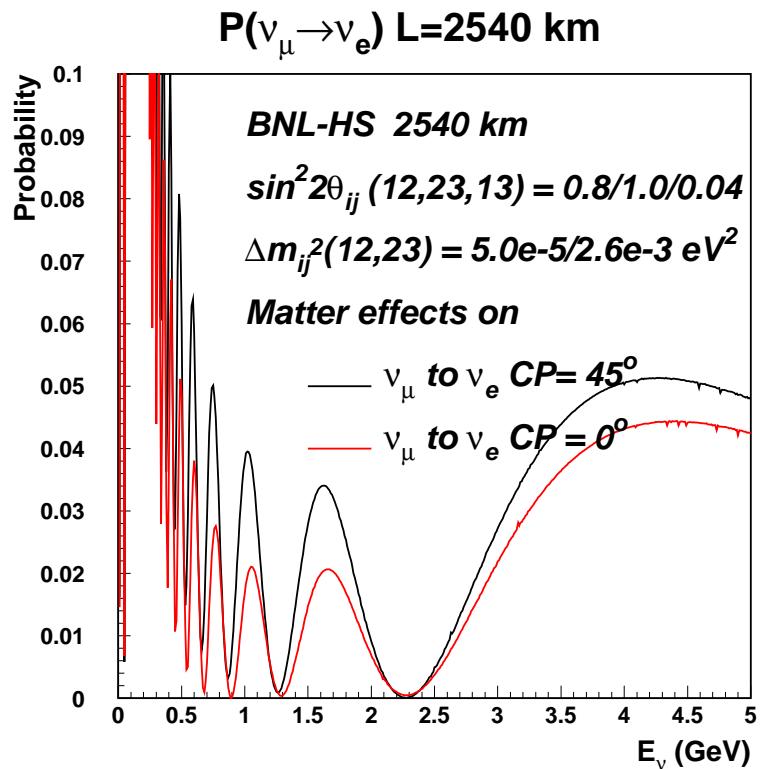
Scaling Laws for CP Measurement

Effect of δ_{CP} compared to first term in appearance.

$R_{CP} \equiv$ Second term divided by First Term.

$$R_{CP} \propto \sin \delta_{CP} \frac{\Delta m_{21}^2 L}{4E} \frac{1}{\sin 2\theta_{13}}$$

- $R_{CP} \propto 1/E$. Matter effect only at high E .
Allows separation of matter effect and CP effect.
- $R_{CP} \propto L$. Event rate $\propto 1/L^2$.
Statistical merit indep. of L for same sized detector.
- $R_{CP} \propto 1/\sin 2\theta_{13}$. Electron event rate $\propto \sin^2 2\theta_{13}$.
Statistical merit indep. of θ_{13} .
- $R_{CP} \propto \Delta m_{21}^2$. Better CP resolution for higher Δm_{21}^2 .
- For given resolution on δ_{CP} detector size is independent of L.

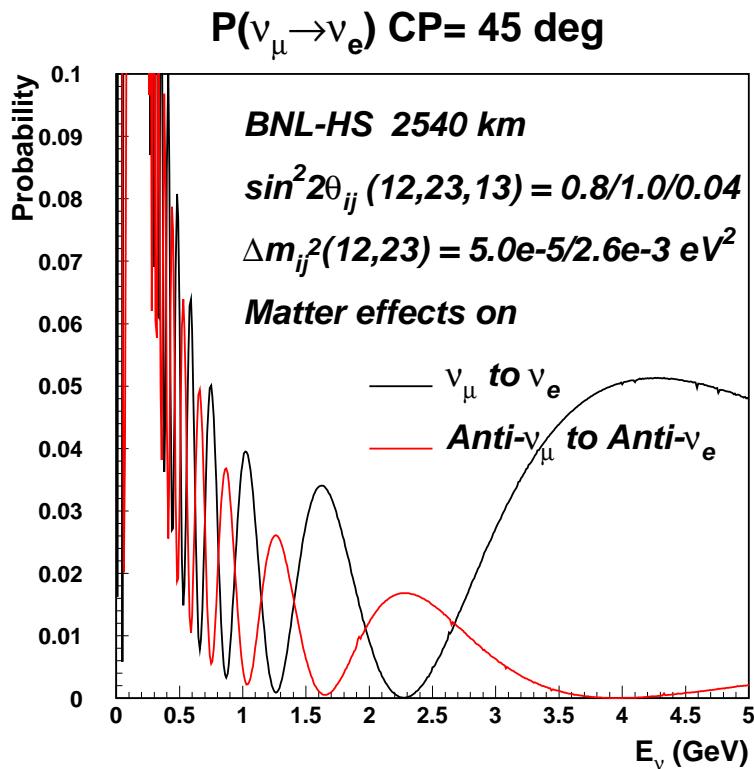


General Features

- 0.5 – 1 GeV: Δm_{12}^2 (LMA) region.
- 1 – 3 GeV: CP large effects region
- > 3 GeV: Matter enhanced (ν_μ), suppressed ($\bar{\nu}_\mu$). ($\Delta m_{32}^2 > 0$) Region.

Exact numerical calculation

e.g. I. Mocioiu and R. Shrock, Phys. Rev. D62, 053017 (2000),
JHEP 0111, 050 (2001)



Compare Neutrino to Antineu.

- 0.5 – 1 GeV: Δm_{12}^2 (LMA) region.
- 1 – 3 GeV: CP region
- > 3 GeV: Matter enhanced (ν_μ), suppressed ($\bar{\nu}_\mu$). ($\Delta m_{32}^2 > 0$) Region.

4 GOALS OF NEUTRINO OSCILLATION PHYSICS

- Precise determination of Δm_{32}^2 and $\sin^2 2\theta_{23}$ and definitive observation of oscillatory behavior.
- Detection of $\nu_\mu \rightarrow \nu_e$ in the appearance mode. If $\Delta m_{\nu_\mu \rightarrow \nu_e}^2 = \Delta m_{32}^2$ then $|U_{e3}|^2 (= \sin^2 \theta_{13})$ is non-zero.
- Detection of the matter enhancement effect in $\nu_\mu \rightarrow \nu_e$. Sign of Δm_{32}^2 ; i.e. which neutrino is heavier.
- Detection of CP violation in neutrino physics. Phase of $|U_{e3}|$ is CP violating and causes asymmetry in the rates $\nu_\mu \rightarrow \nu_e$ versus $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$.

It will be good to do it all in same experiment with only neutrino beam (no antineutrino).

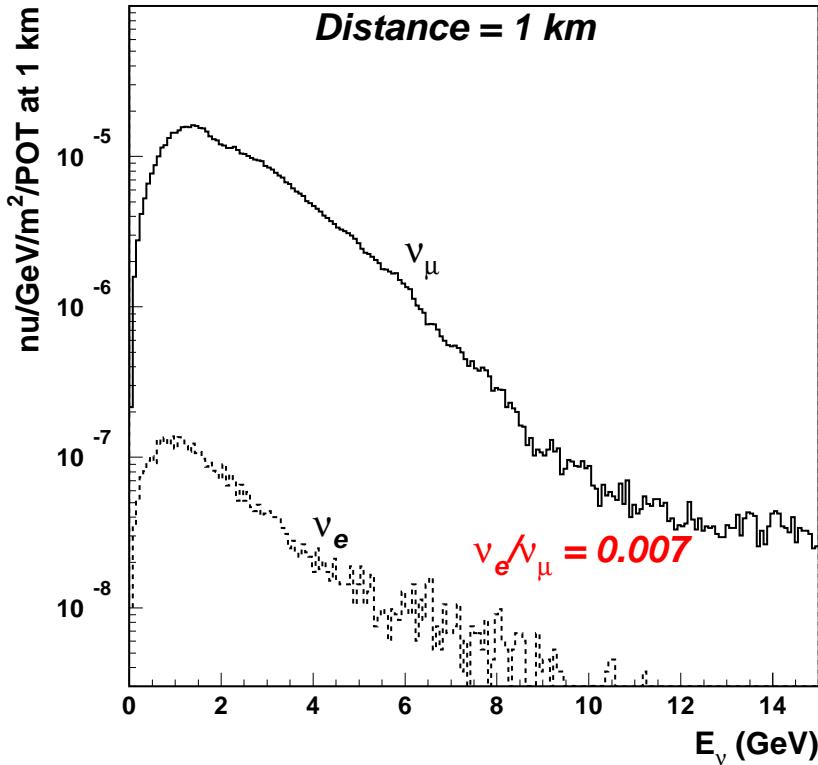
Summary of our study

- Baseline of > 2000 km with wide band conventional beams are the next step in accelerator neutrino physics.
- Extraordinary, large physical effects will be seen in such an experiment.
- Very good sensitivity to neutrino properties.
 - $< 1\%$ resolution on Δm_{32}^2
 - $< 1\%$ resolution on $\sin^2 2\theta_{23}$
 - Sensitivity to $\sin^2 2\theta_{13} > 0.005$ over a wide range of Δm_{32}^2
 - Sensitivity to CP violation.
 - Sign of Δm_{32}^2 over a wide range of parameters.
 - Measurement of Δm_{21}^2 in LMA region.
- Requires new thinking on how to build a beam and a detector. But experiment is technically feasible.

Comments

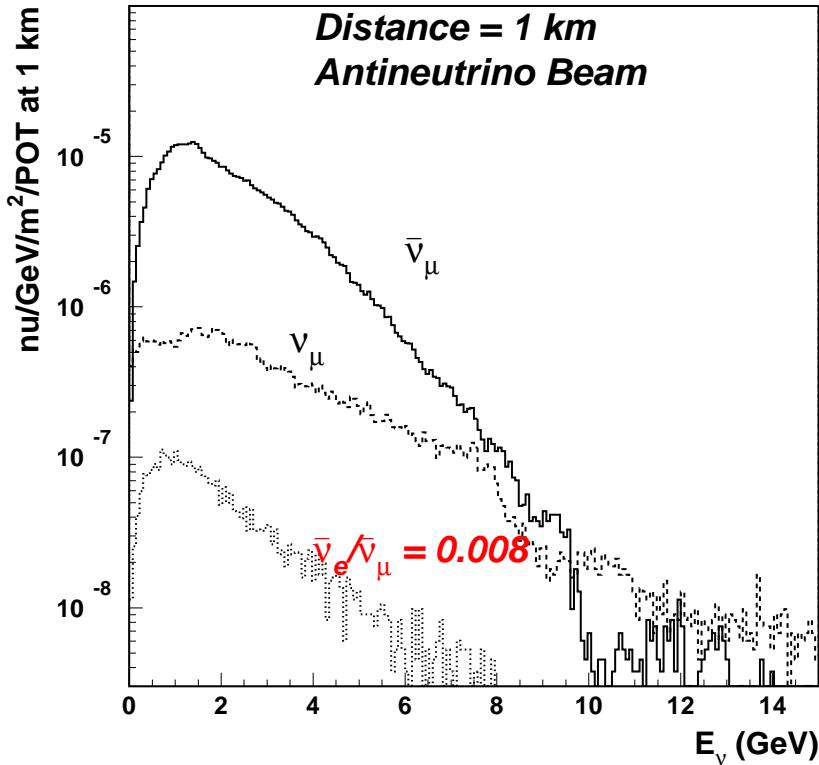
- Important ideas here are:
 - Long baseline to achieve large effects
 - Low energy wide band beam to get spectra
 - Beam is wide band, but low energy to make low backgrounds to ν_e appearance signature.
- Important difference between quark-matrix and neutrino-matrix
 - Neutrino oscillation effects are exactly calculable for any given set of parameters.
(including matter)
 - For quarks we often need complex tools such as CHPT and Lattice to connect CKM-matrix to physical phenomena.
- It makes sense to make a neutrino oscillation experiment with large effects even if they are sensitive to multiple parameters.

BNL Wide Band. Proton Energy = 28 GeV



- New design spans 0.5-6 GeV
- Low ν_e background 0.7%
 0.0073 ± 0.0014 (E734 1986).
- Low background from high energies (NC and ν_τ for ν_e)
- 200 m decay tunnel
- Graphite target embedded in horn
- Target cooling achievable for 1 MW

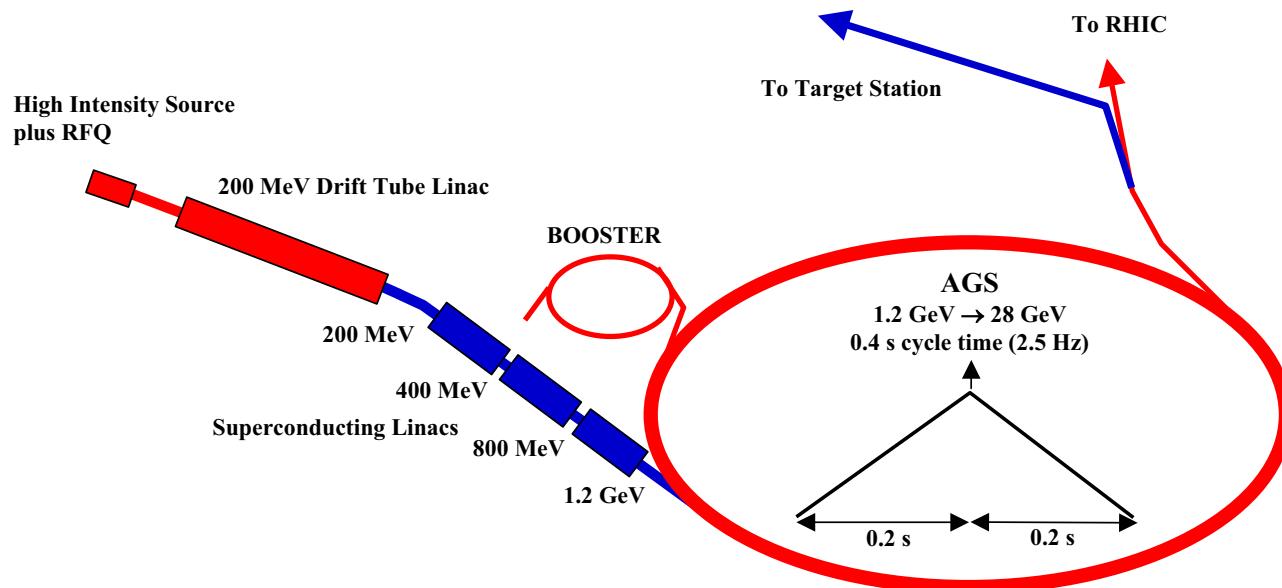
BNL Wide Band. Proton Energy = 28 GeV



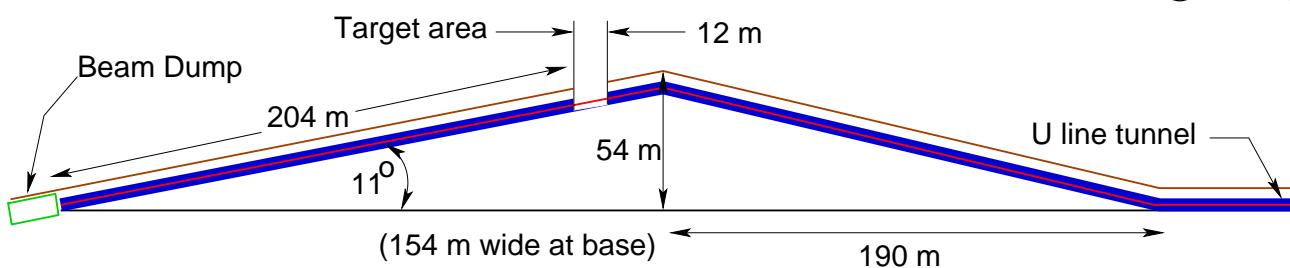
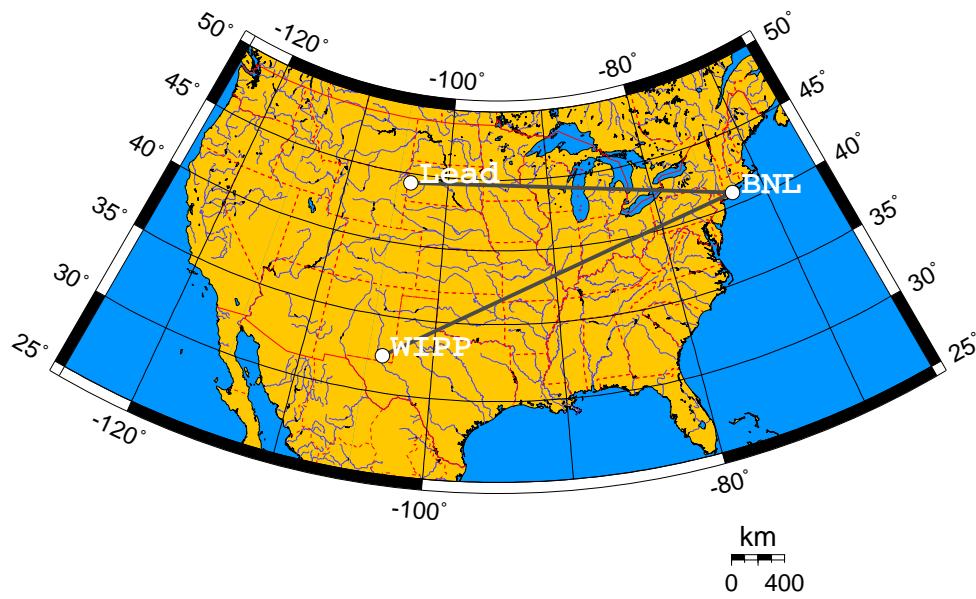
- Antineutrino beam has larger neutrino contamination.
- Will need to go to 2 MW to get statistics equal to neutrino.

The Accelerator

- Conceptually simple upgrade. No magic.
- Run 28 GeV AGS at 2.5 Hz to get 1 MW.
- Need faster proton source: Super Conducting LINAC at 1.2 GeV
- Current: $7 \times 10^{13} ppp$ at 0.5 Hz => LINAC: $10^{14} ppp$ at 2.5 Hz.



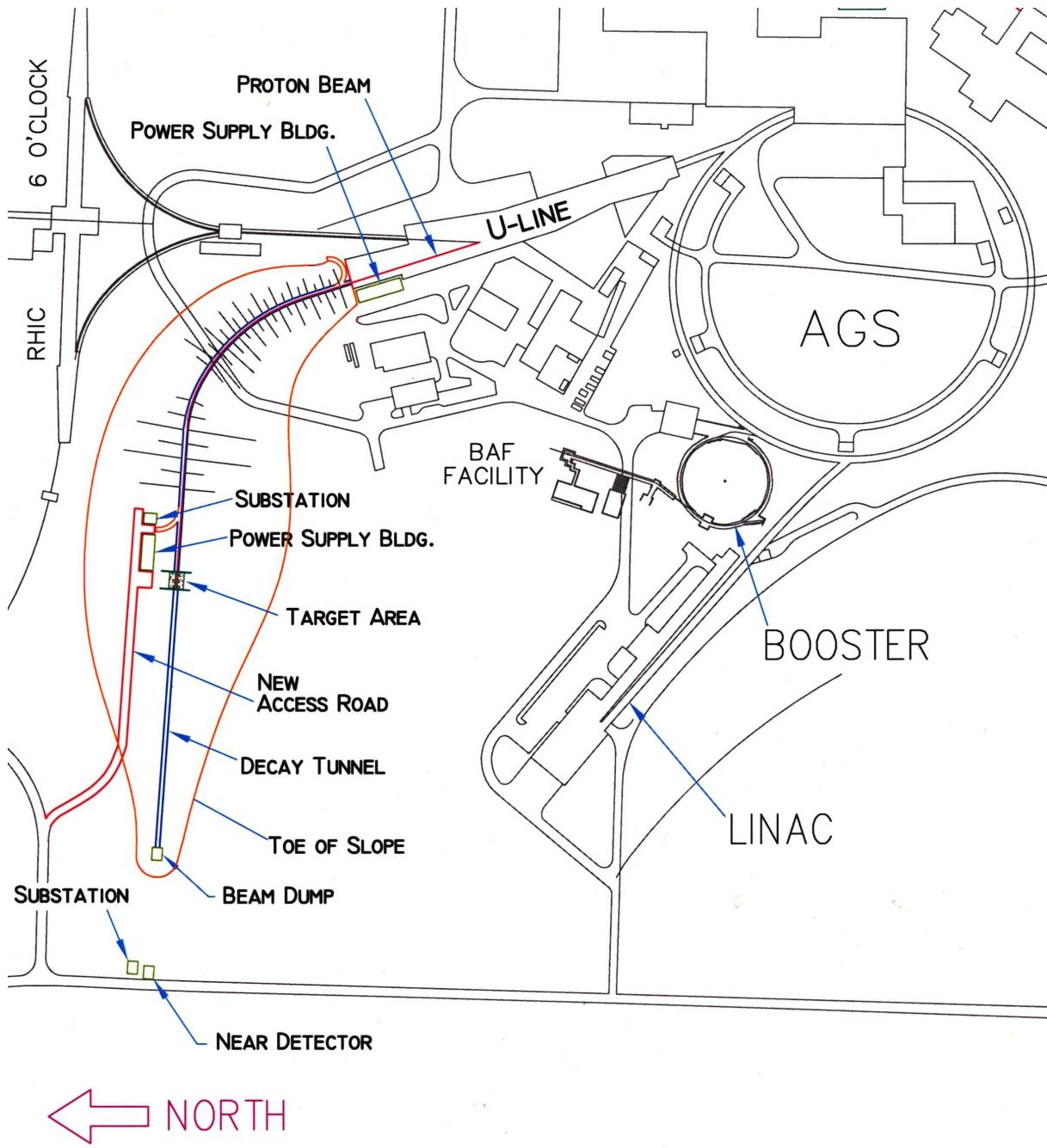
Beam on the Hill



- BNL-Lead 2540km
BNL-Wipp: 2880km
- Avoids water table.
- Hills are inexpensive:
highway ramps.

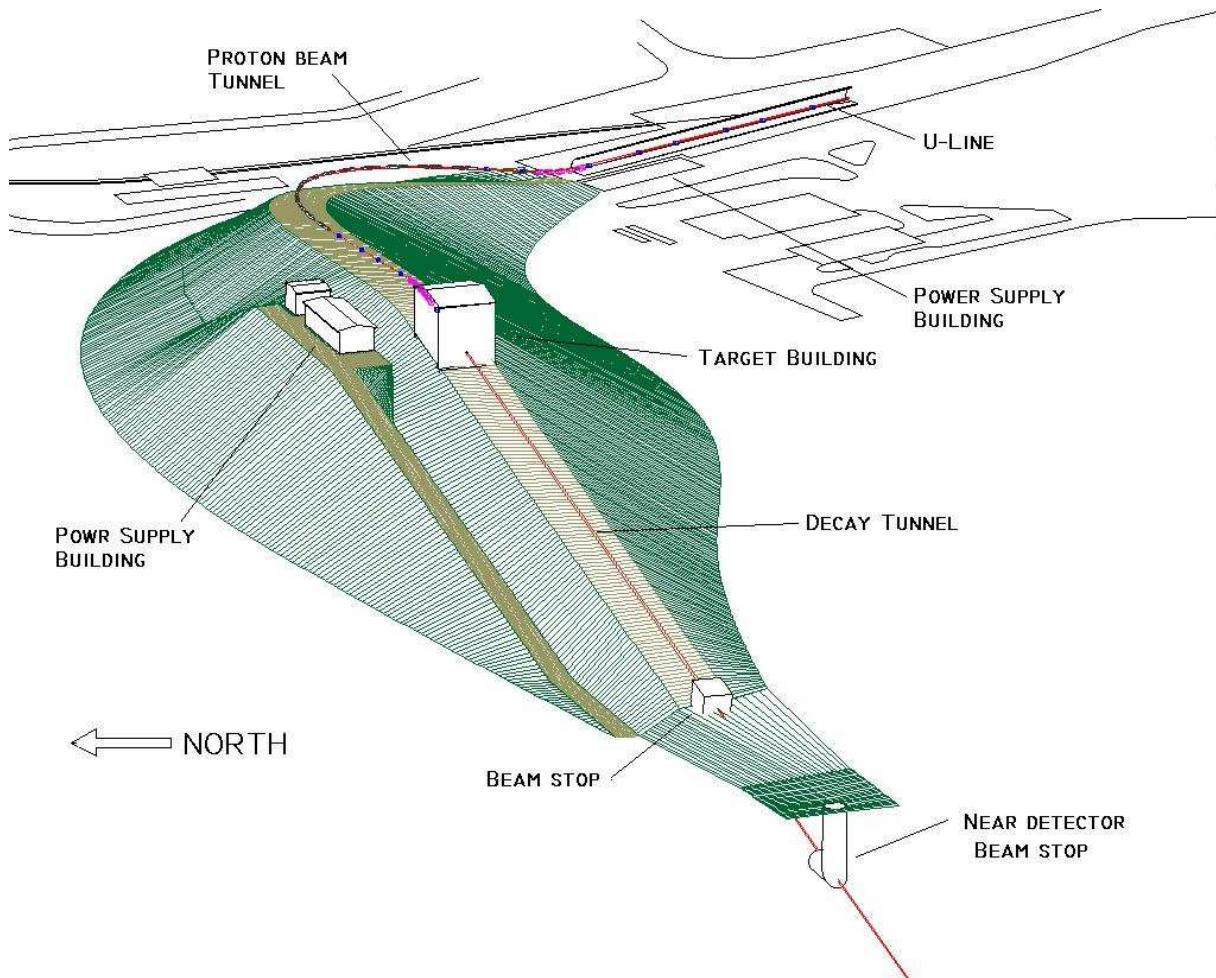
Very long baselines with a superbeam

Beam Layout

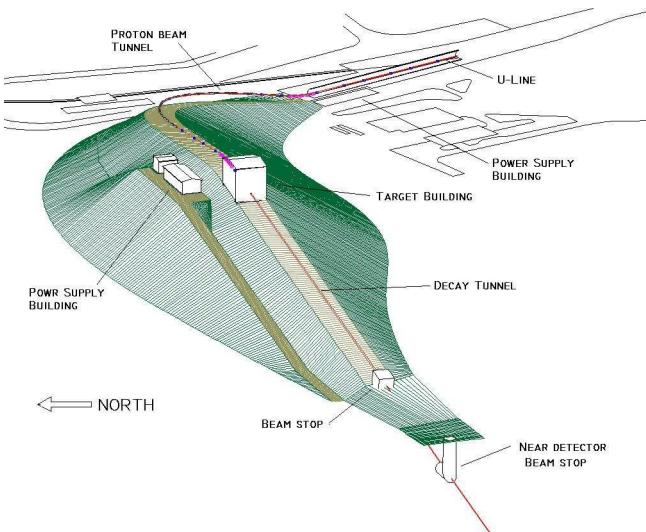
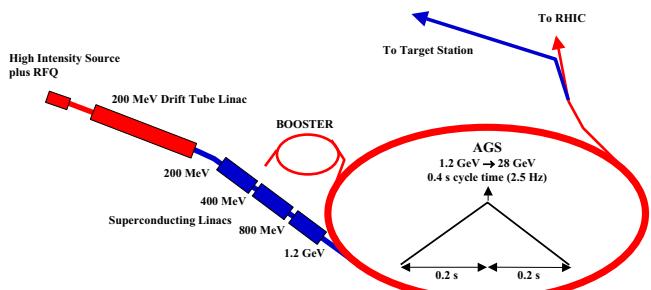


Very long baselines with a superbeam

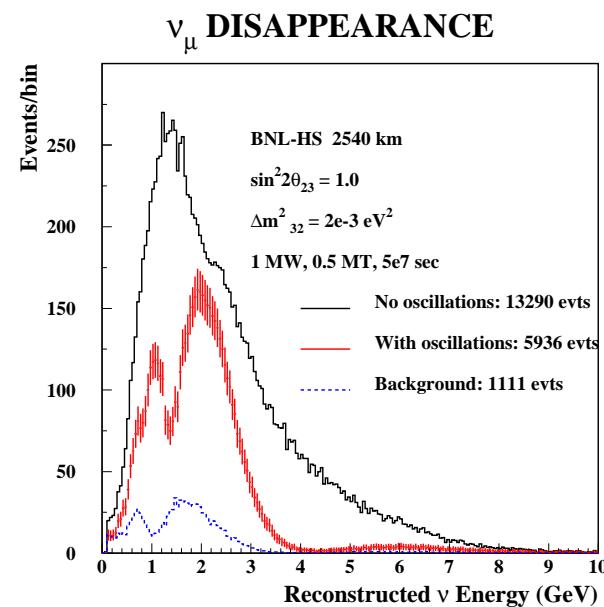
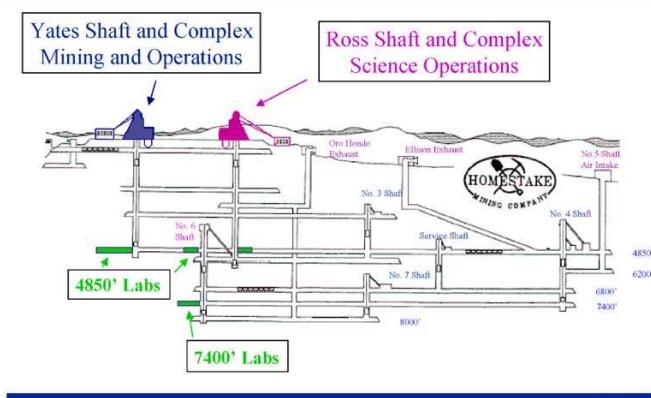
Beam 3d



1 MW beam - 2540 km - 500 kT detector



NUSL Overview (cross-section)



Event Rates with Neutrinos

Assume 1 MW, 500 kT Fiducial, 5×10^7 sec running. (1.22×10^{22} Protons at 28 GeV.)

Assume Water Cerenkov detector.

CC $\nu_\mu + N \rightarrow \mu^- + X$	51800 (15160)
NC $\nu_\mu + N \rightarrow \nu_\mu + X$	16908 (5770)
CC $\nu_e + N \rightarrow e^- + X$	380 (103)
QE $\nu_\mu + n \rightarrow \mu^- + p$	11767 (5934)
QE $\nu_e + n \rightarrow e^- + p$	84 (40)
CC $\nu_\mu + N \rightarrow \mu^- + \pi^+ + N$	14574 (4200)
NC $\nu_\mu + N \rightarrow \nu_\mu + N + \pi^0$	3178 (1156)
NC $\nu_\mu + O^{16} \rightarrow \nu_\mu + O^{16} + \pi^0$	574 (202)
CC $\nu_\tau + N \rightarrow \tau^- + X$ (depends on Δm^2)	~ 110 (20)

Backgrounds to clean (QE) events SMALL

NC dominated by elastic and single π .

Low τ production.

Anti-neutrino rate in (brackets) for 1 MW. Neutrino contamination additional.

Neutral Current Events Neutrinos

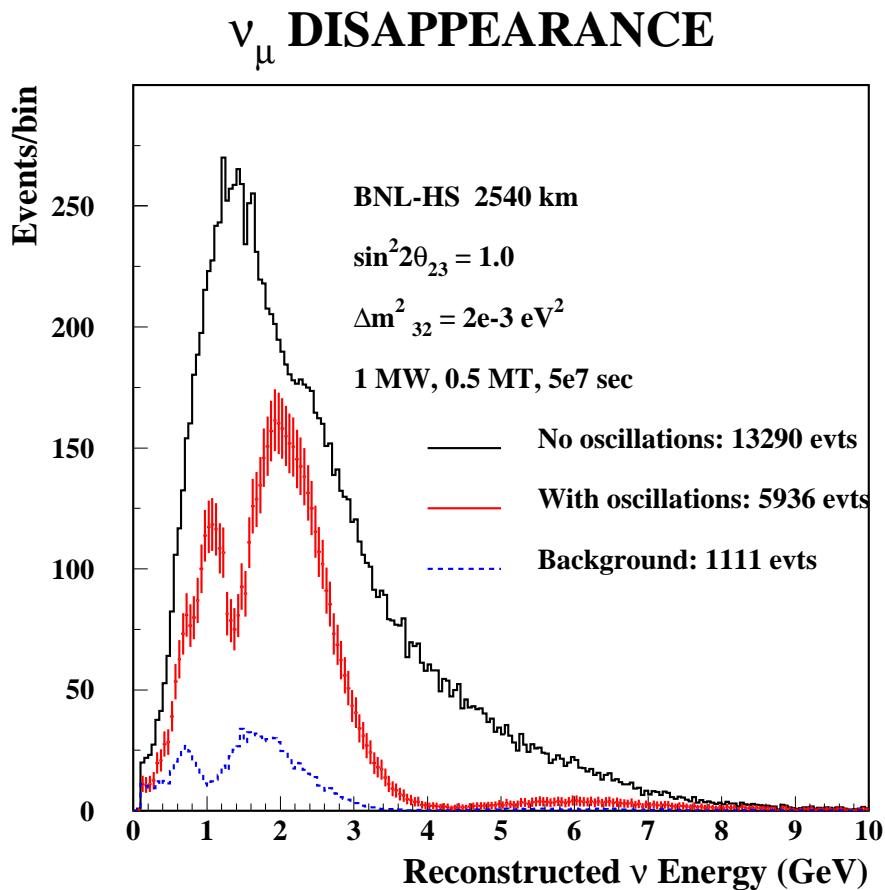
Assume 1 MW, 500 kT Fiducial, 5×10^7 sec running. (1.22×10^{22} Protons at 28 GeV.)

Assume Water Cerenkov detector (with $\sim 10\%$ PMT coverage)

NC $\nu_\mu + N \rightarrow \nu_\mu + X$	16908
Single π^0	3700
Single π^\pm	3500
$\nu + n \rightarrow \nu + n$	2000
$\nu + p \rightarrow \nu + p$	2000
Multi-pi (0 π^0)	2900
Multi-pi ($\geq 1 \pi^0$)	2900

Multiple pion events should be suppressed better than single π^0 events.

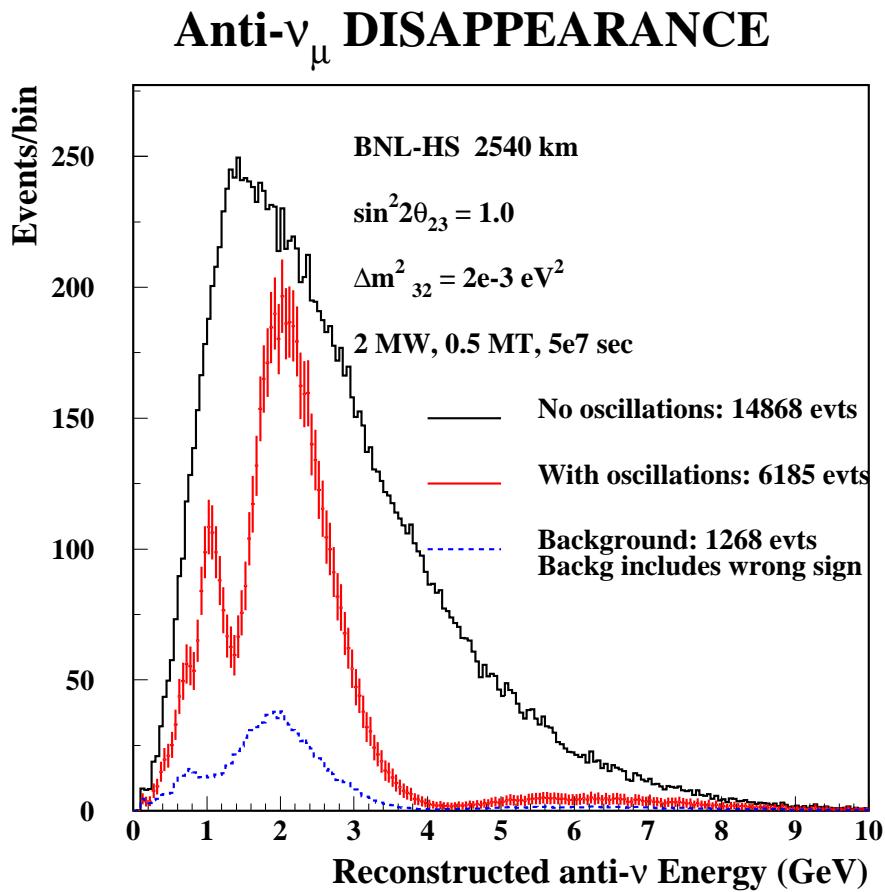
Both single and multi-pi event rate display the same tendency to fall rapidly with energy.



Node pattern provides high Δm^2_{32} resolution.
Energy calibration is very important.

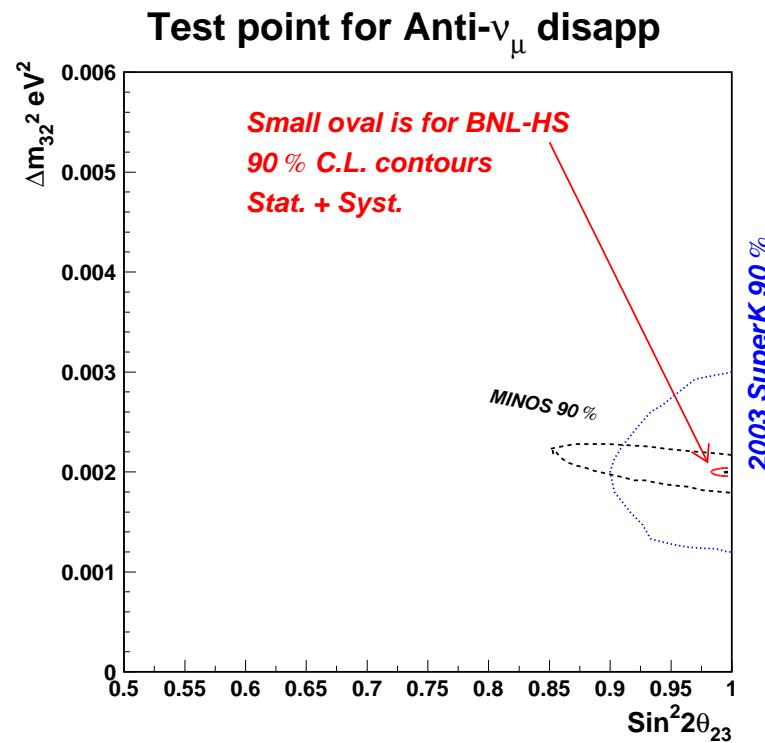
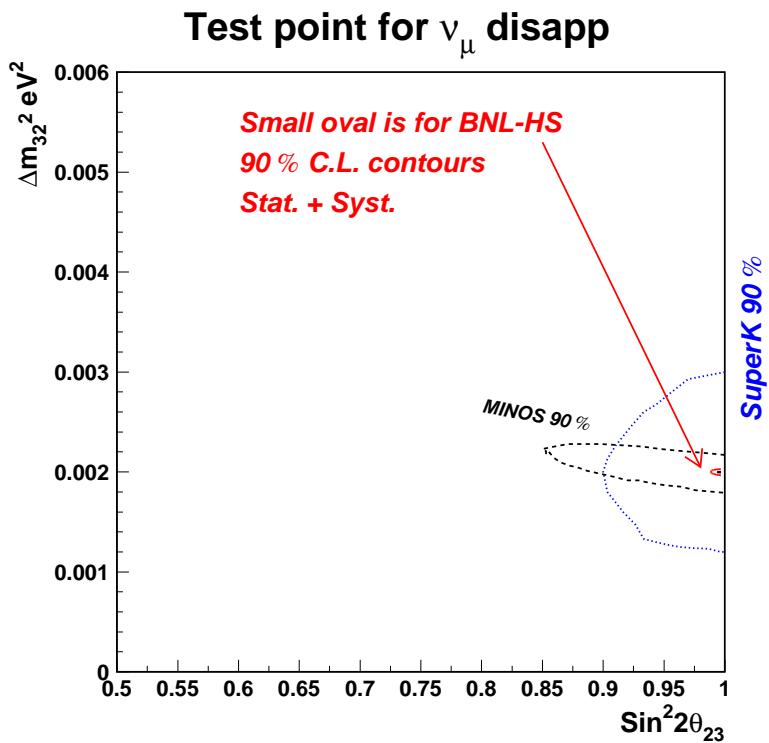
Flux normalization not important for
measurement of $\sin^2 2\theta_{23}$

Background shape can be measured independently
Minimum systematics in ν_μ and $\bar{\nu}_\mu$ comparison



For anti-neutrinos low energy nodes have less statistics because of cross section.

Very long baselines with a superbeam

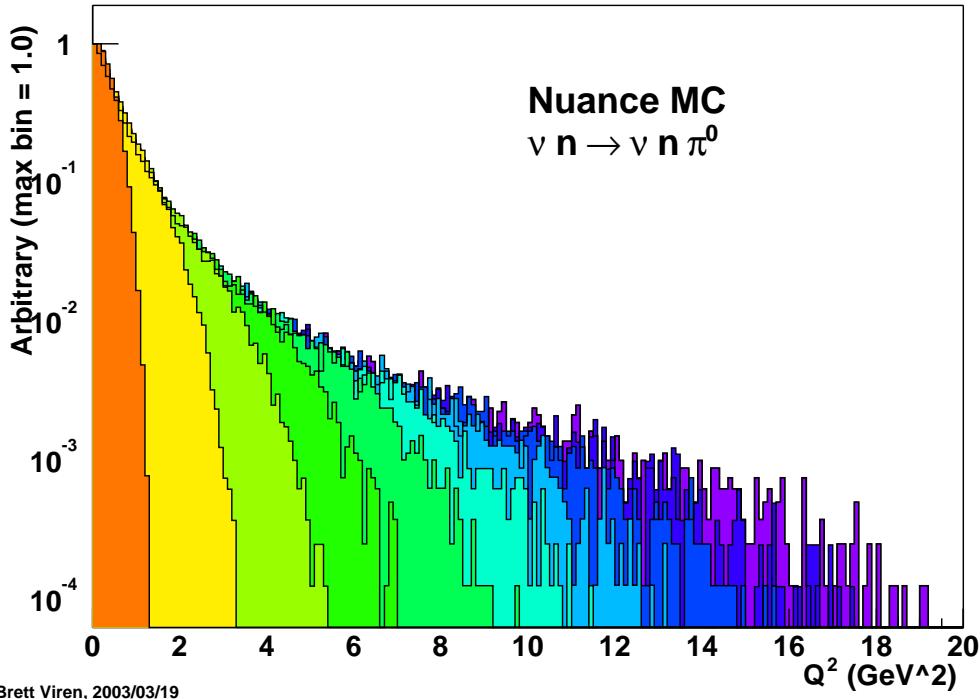


Measurement of Δm_{32}^2

- Little dependence on systematic errors on resolution, backgrounds, energy linearity, or normalization.
- Ultimate resolution on Δm^2 depends on energy calibration. For perfect energy calibration $\pm 0.7\%$ possible.
- Energy calibration at $< 1\%$ in 1-5 GeV region needed.
- Can exclude $\sin^2 2\theta_{23} < 0.99$ at 90% C.L.
Could be better with accurate background subtraction.
- No need of near detector for this measurement. Even a 10% systematic error on normalization does not bother measurement.
- neutrino-antineutrino comparison free of most systematics (even cross section) because of nodal pattern. Possible to measure difference in Δm_{32}^2 of $< 1\%$.

NC π^0 background for $\nu_\mu \rightarrow \nu_e$

Q^2 for $E_\nu = 1\text{-}10 \text{ GeV}$



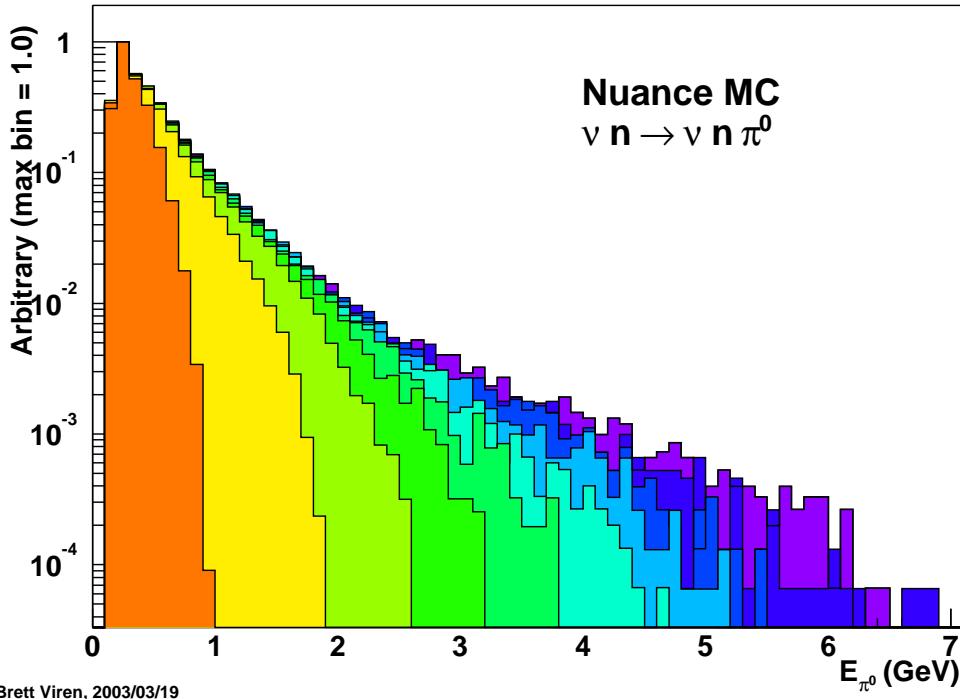
$$q^2 = (p'_N + p'_\pi) - p_N.$$

General feature of all neutral current processes:

Low q^2 or low hadronic energy in final state independent of neutrino energy.

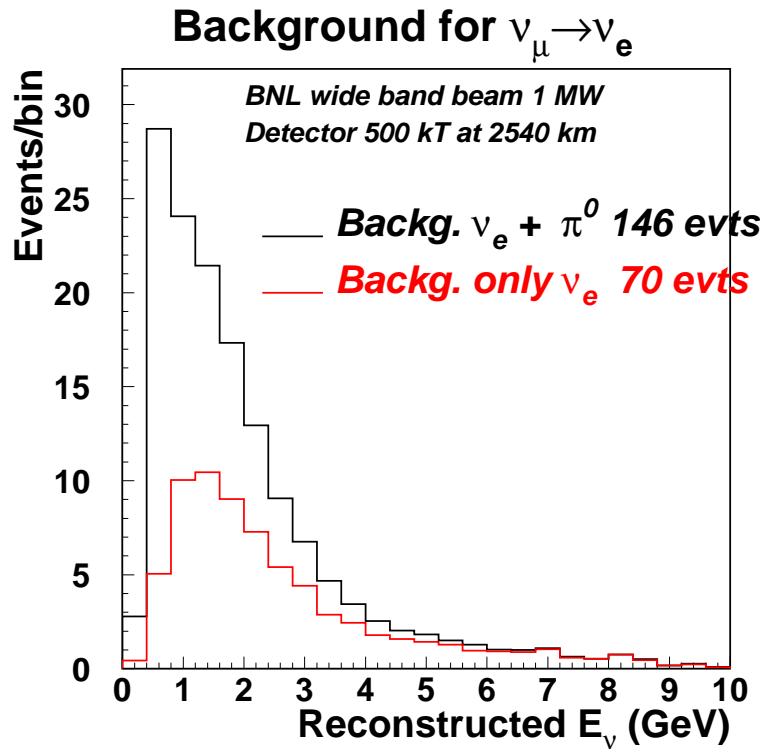
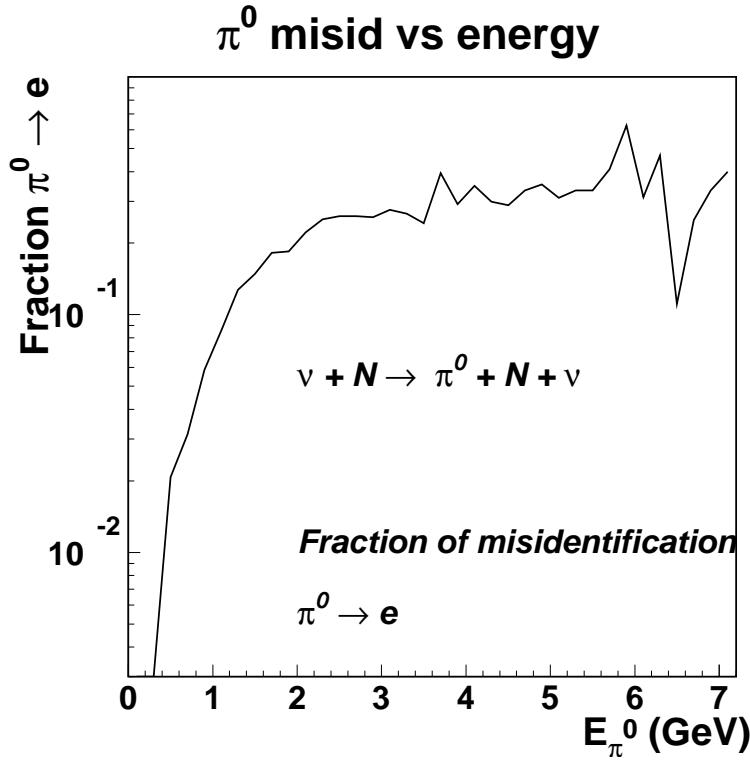
NC π^0 background for $\nu_\mu \rightarrow \nu_e$

E_{π^0} for $E_\nu = 1\text{-}10 \text{ GeV}$



- The NC energy distribution is independent of ν -energy except the kinematic limit.
- In $\nu_\mu N \rightarrow \nu_\mu N \pi^0$ events all energy ν produce peak at the same energy except the tail.
- For a very long baselines and wide band beam ν_e signal will be above 3 GeV with little π^0 background.

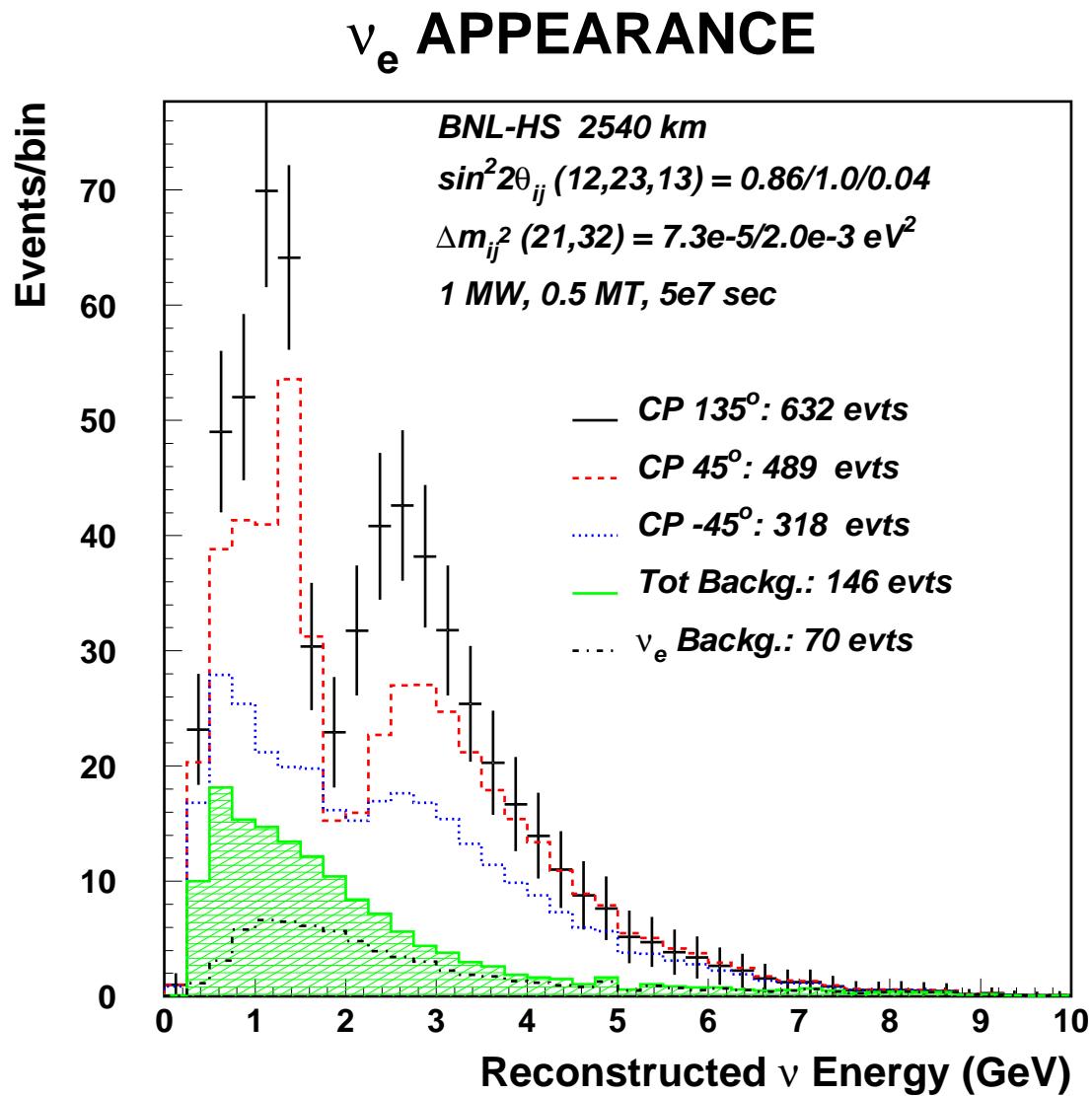
$\nu_\mu \rightarrow \nu_e$ All background



- Background includes $\nu N \pi^0$ and Coherent $\nu O^{16} \pi^0$.
- Efficiency for signal is $\sim 80\%$
- For $E_\nu < 2\text{GeV}$ $N_{\pi^0} : N_{\nu_e} :: 59 : 35$
- For $E_\nu > 2\text{GeV}$ $N_{\pi^0} : N_{\nu_e} :: 17 : 35$

Very long baselines with a superbeam

Measurement of $\sin^2 2\theta_{13}$

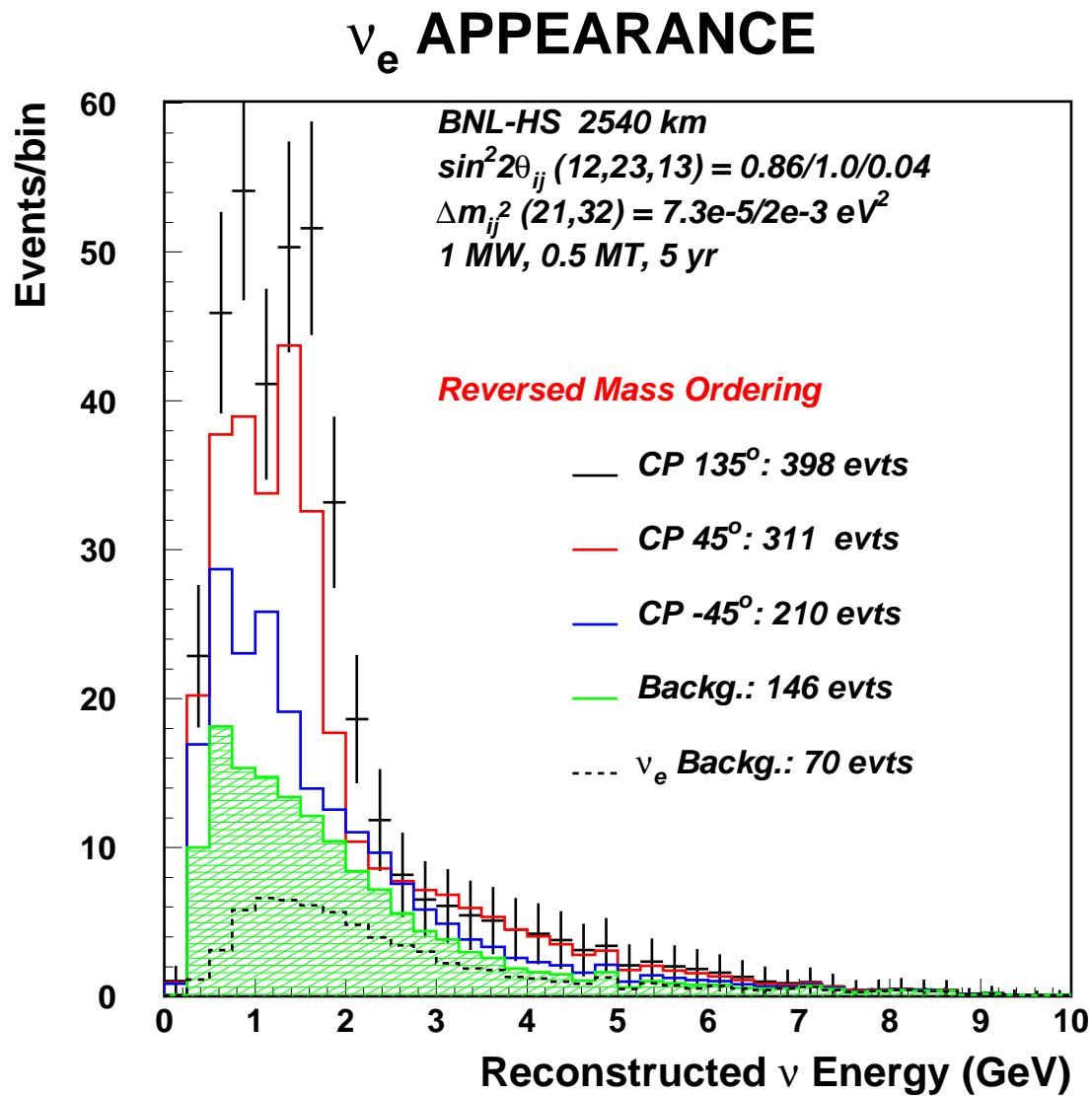


$$\Delta m_{32}^2 = 0.002 \text{ eV}^2, \sin^2 2\theta_{13} = 0.04.$$

Assume normal mass hierarchy. $m_3 > m_2 > m_1$

Matter effects included.

Measurement of $\sin^2 2\theta_{13}$

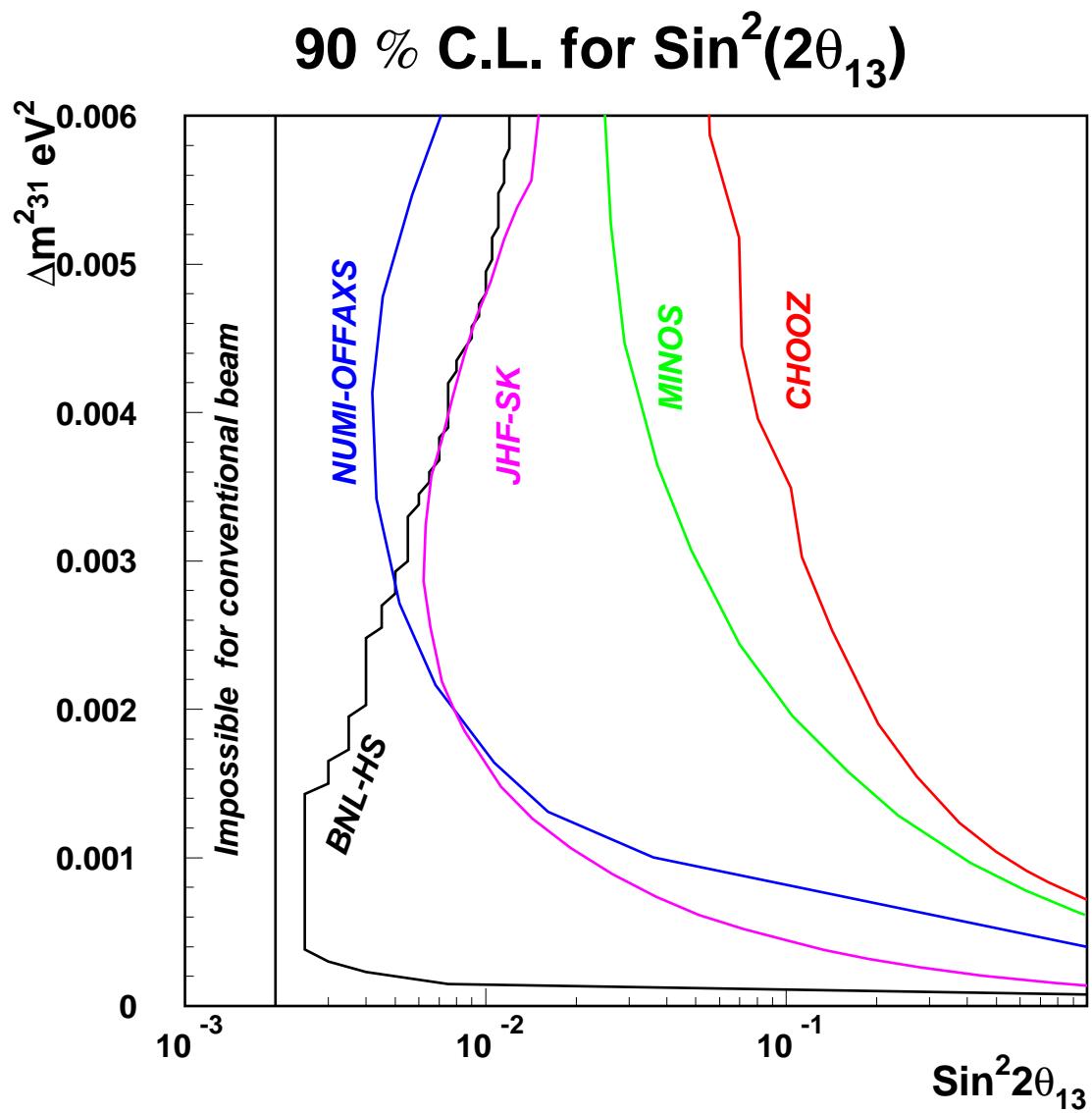


$$\Delta m_{32}^2 = 0.002 \text{ eV}^2, \sin^2 2\theta_{13} = 0.04.$$

Reversed Mass Hierarchy

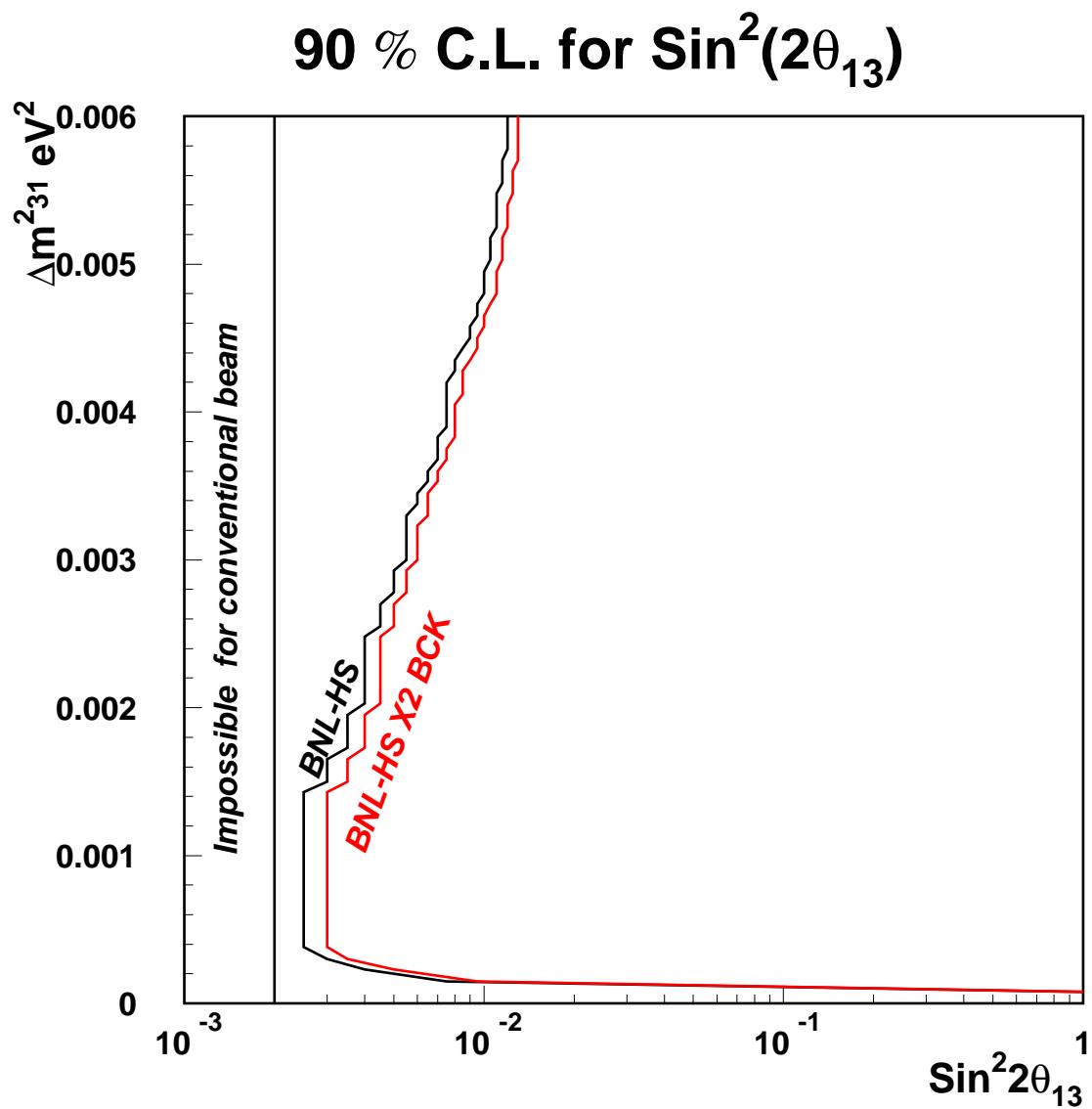
Matter effects included.

Measurement of $\sin^2 2\theta_{13}$ 90% C.L.



Distinctive signature with multiple oscillations
above 0.001 eV^2

Measurement of $\sin^2 2\theta_{13}$ 90% C.L. high Bckg.



Assume that the neutral current background is higher by factor of 2 over the entire spectrum.

Measurement of $\sin^2 2\theta_{13}$ 90% C.L.

BNL-HS(2540 km) good sensitivity to $\sin^2 2\theta_{13}$.

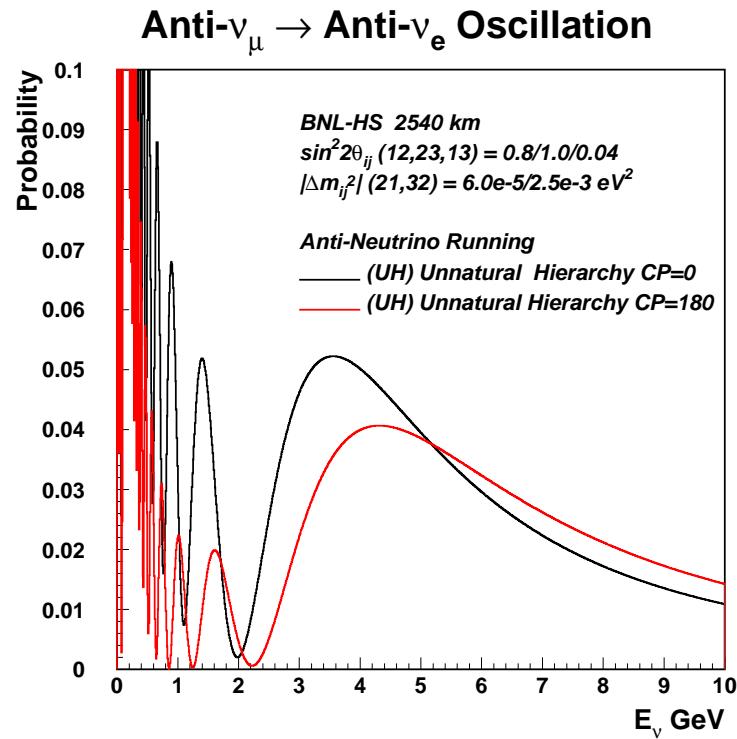
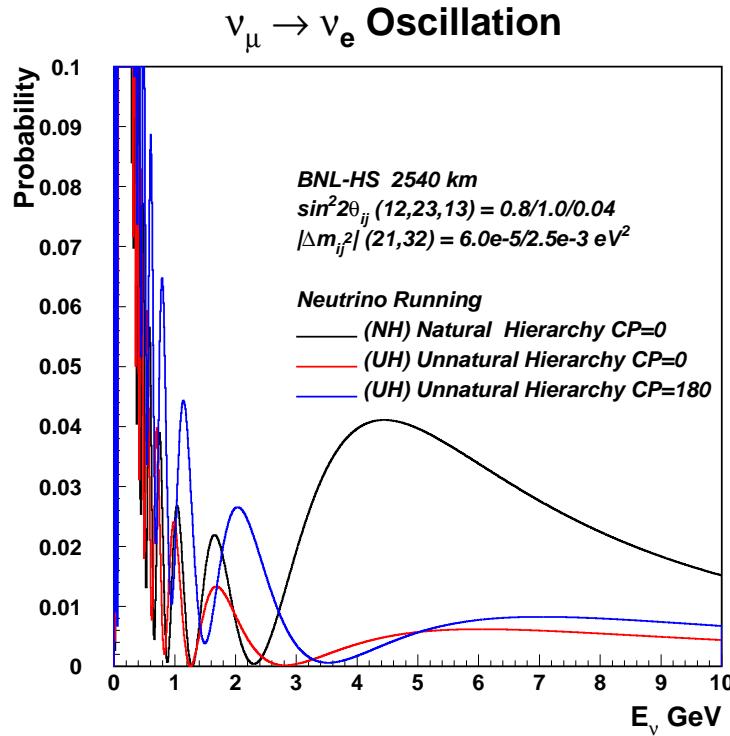
Improvement from 0.12 to 0.005 at 0.0025 eV^2 .

Signal very distinctive above 0.001 eV^2 .

Need harder beam to improve sensitivity above 0.004 eV^2 .

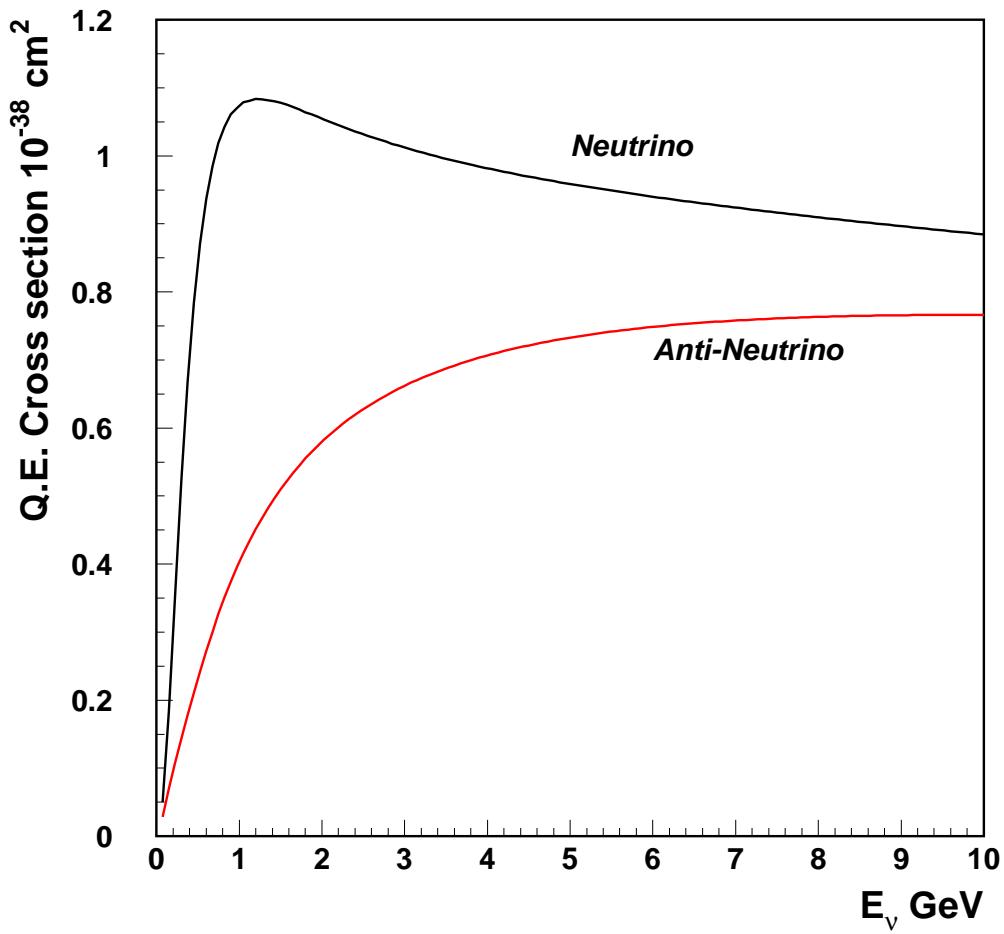
No experiment can go below $\sin^2 2\theta_{13} \approx 0.002$ with horn focussed beam due to systematic error on intrinsic ν_e background.

Mass Hierarchy Anti-neutrinos



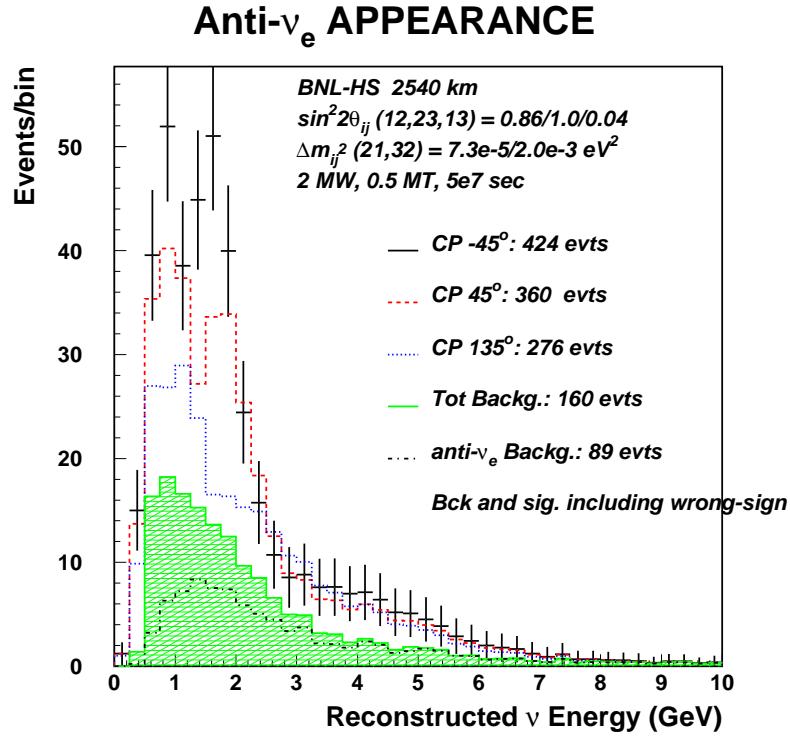
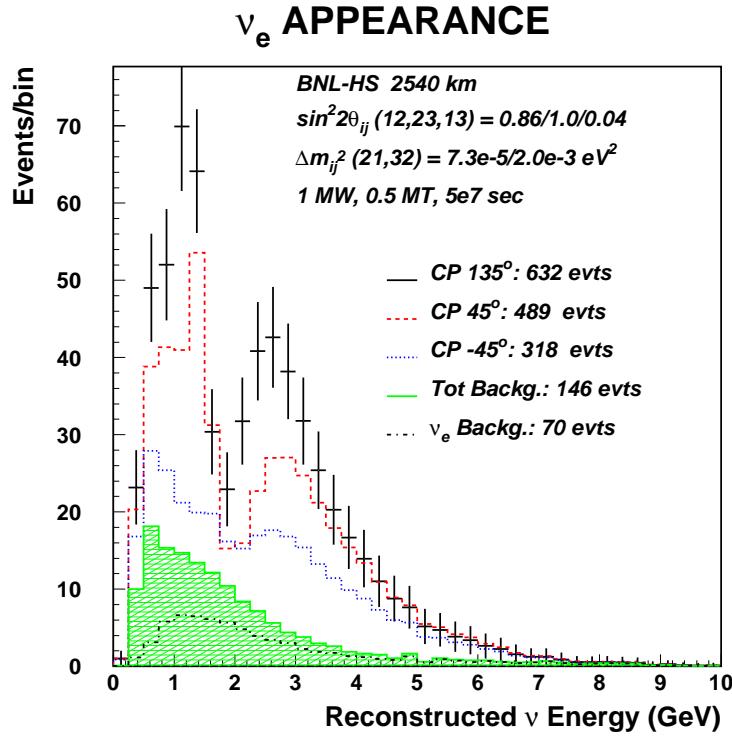
Very long baselines with a superbeam

Quasielastic cross section



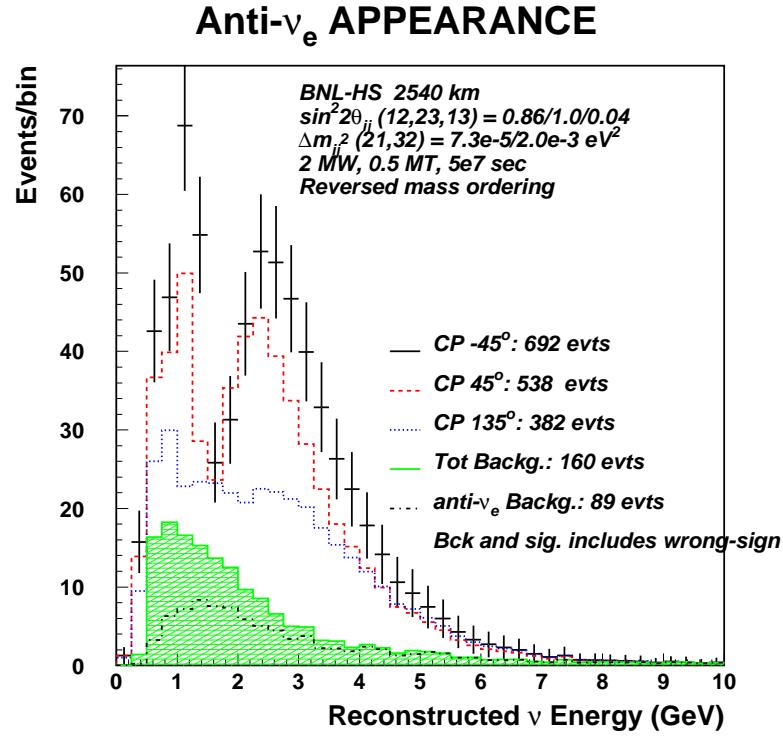
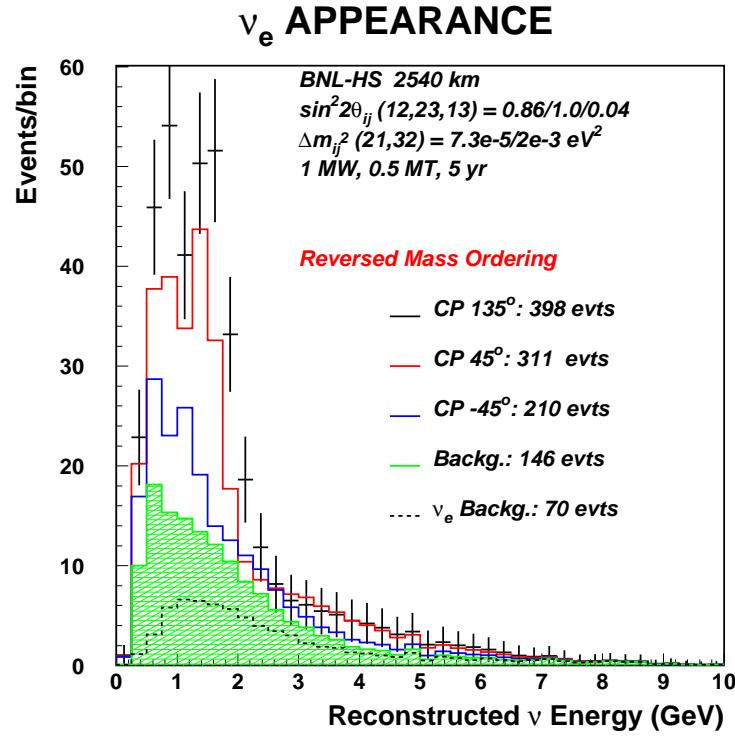
An experiment searching for signal at high energies may not need much more anti-neutrino running than neutrino running.

Running for $\sin^2 2\theta_{13}$



$\Delta m_{32}^2 = 0.002 \text{ eV}^2$, $\sin^2 2\theta_{13} = 0.04$. Assume normal mass hierarchy. $m_3 > m_2 > m_1$ Matter effects included.

Running for $\sin^2 2\theta_{13}$



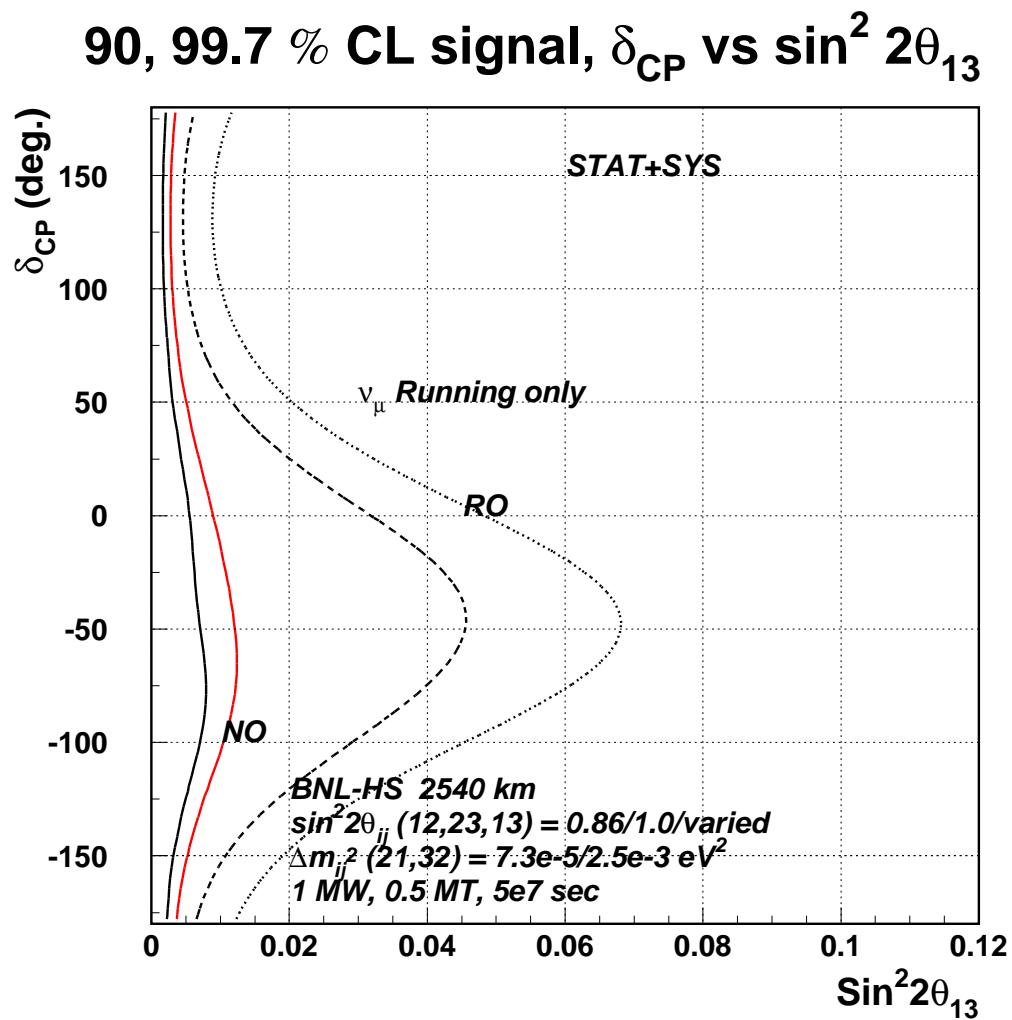
$$\Delta m_{32}^2 = 0.002 \text{ eV}^2, \sin^2 2\theta_{13} = 0.04.$$

Reversed Mass Hierarchy

Matter effects included.

Very long baselines with a superbeam

Mass Hierarchy



Natural Mass hierarchy: $m_3 > m_2 > m_1$ (NO)

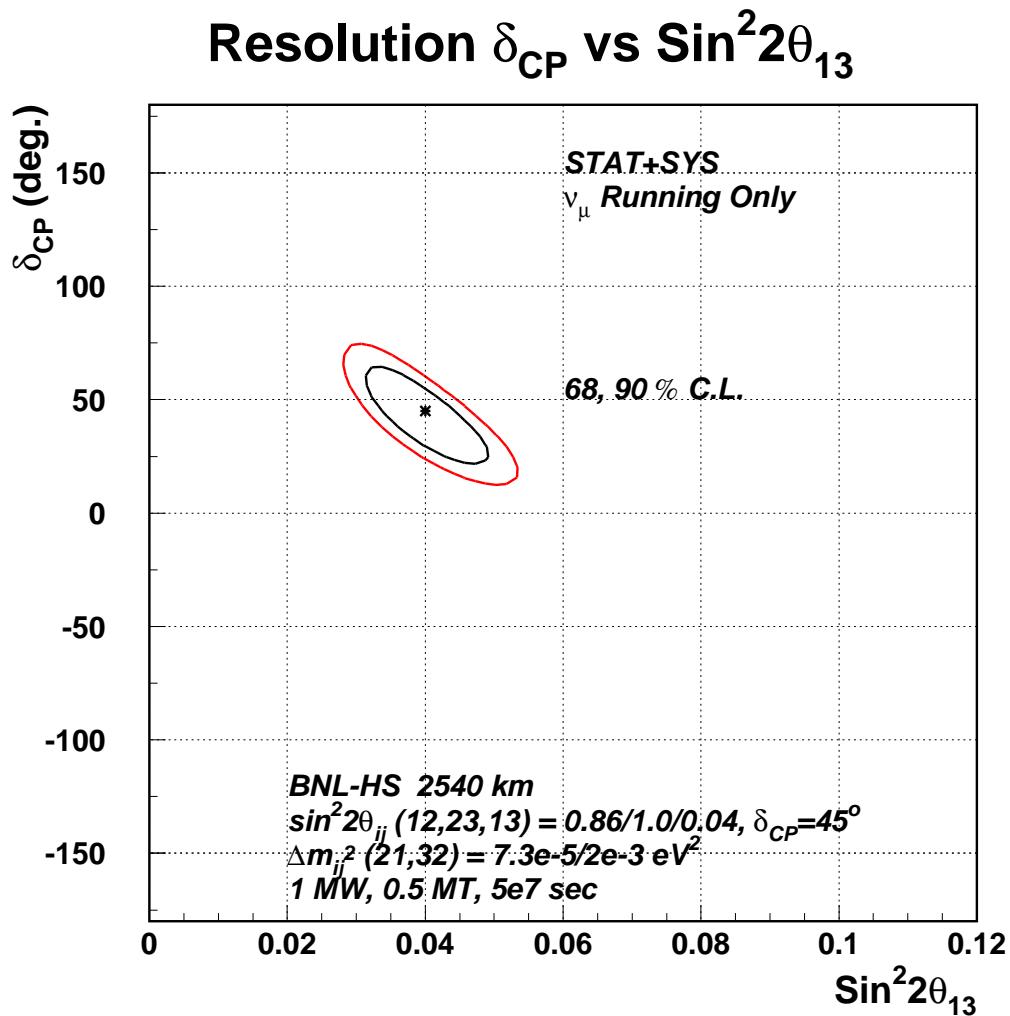
Reversed Mass hierarchy: $m_1 > m_2 > m_3$ (RO)

Unnatural Mass hierarchy: $m_2 > m_1 > m_3$ (RO)

$m_1 > m_2$ is ruled out if Solar LMA is the correct solution.

We would need to run Anti-neutrino beam to fully explore RO.

Measurement of $\delta_{CP} = 45^\circ$
No anti-neutrino running.



Systematic error of 10% on backg.

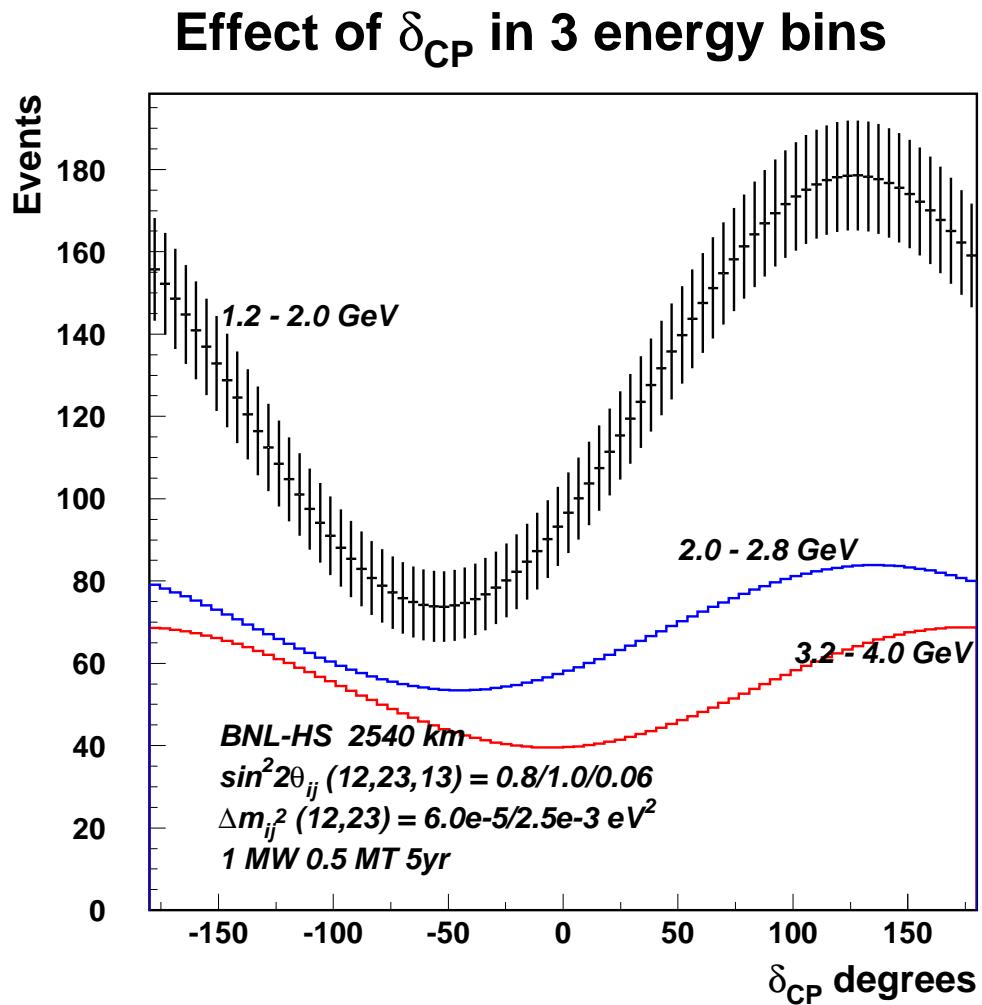
$$\Delta m_{21}^2 = 7.3 \times 10^{-5} \text{ eV}^2, \Delta m_{31}^2 = 2 \times 10^{-3} \text{ eV}^2$$

$$\sin^2 2\theta_{12} = 0.86, \sin^2 2\theta_{23} = 1.0$$

$$\delta_{CP} = 45^\circ, \sin^2 2\theta_{13} = 0.04$$

68%, and 90% C.L.

Effect of δ_{CP} on the spectrum.



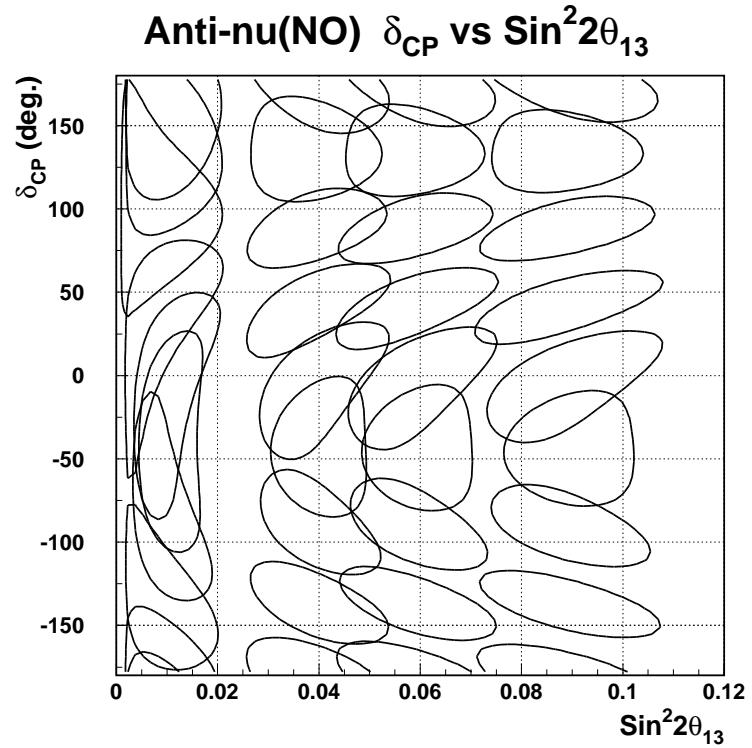
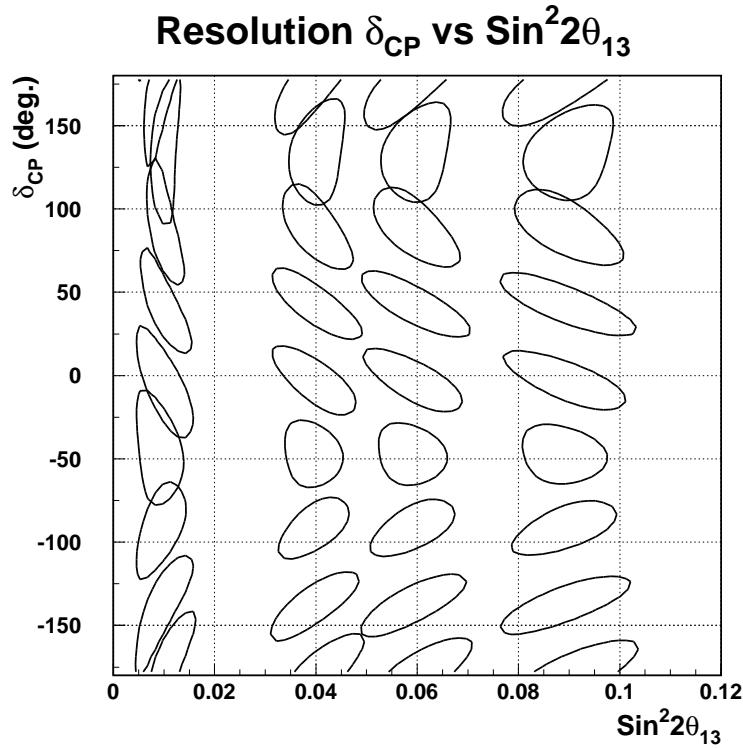
Event rate in 3 energy bins.

$$\Delta m_{21}^2 = 6 \times 10^{-5} \text{ eV}^2, \Delta m_{31}^2 = 2.5 \times 10^{-3} \text{ eV}^2$$

$$\sin^2 2\theta_{12} = 0.8, \sin^2 2\theta_{23} = 1.0$$

$$\sin^2 2\theta_{13} = 0.06$$

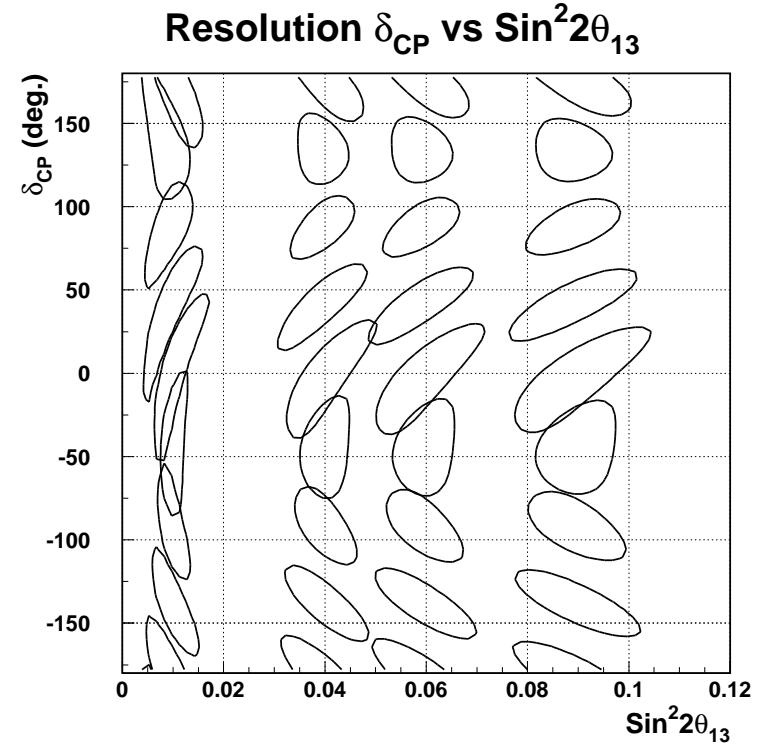
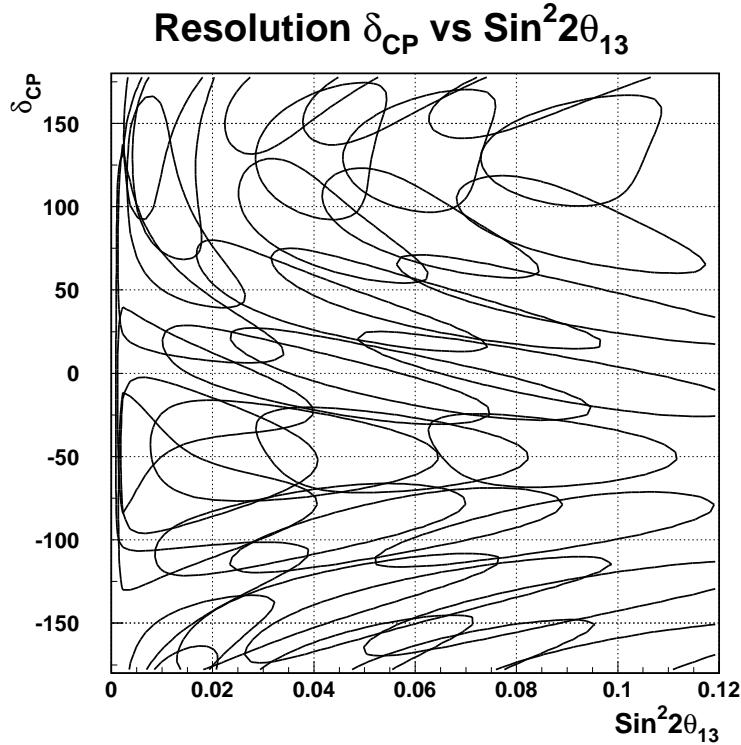
Error on δ_{CP} vs $\sin^2 2\theta_{13}$



$$\Delta m_{21}^2 = 7.3 \times 10^{-5} eV^2, \Delta m_{31}^2 = 2 \times 10^{-3} eV^2$$

$$\sin^2 2\theta_{12} = 0.86, \sin^2 2\theta_{23} = 1.0$$

Error on δ_{CP} vs $\sin^2 2\theta_{13}$



Reversed hierarchy.

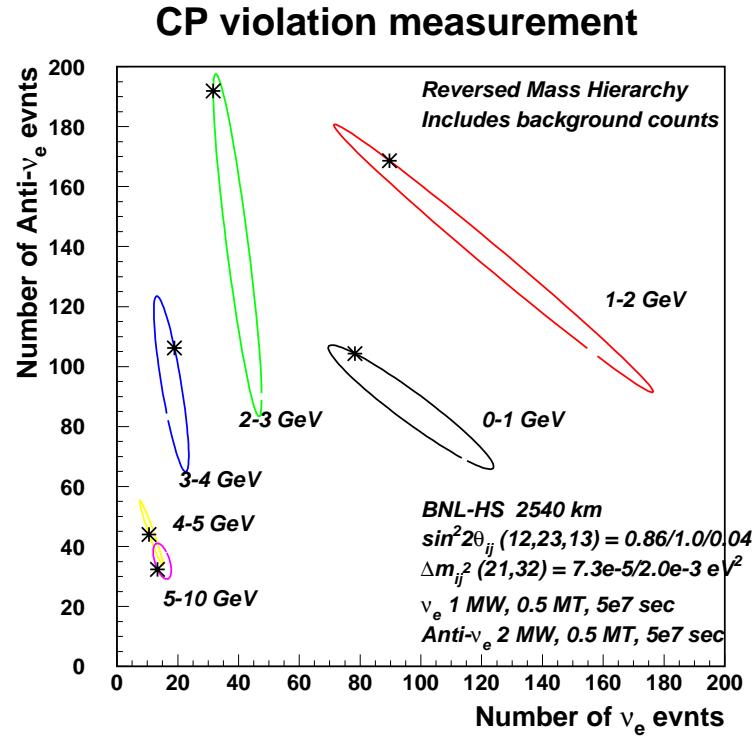
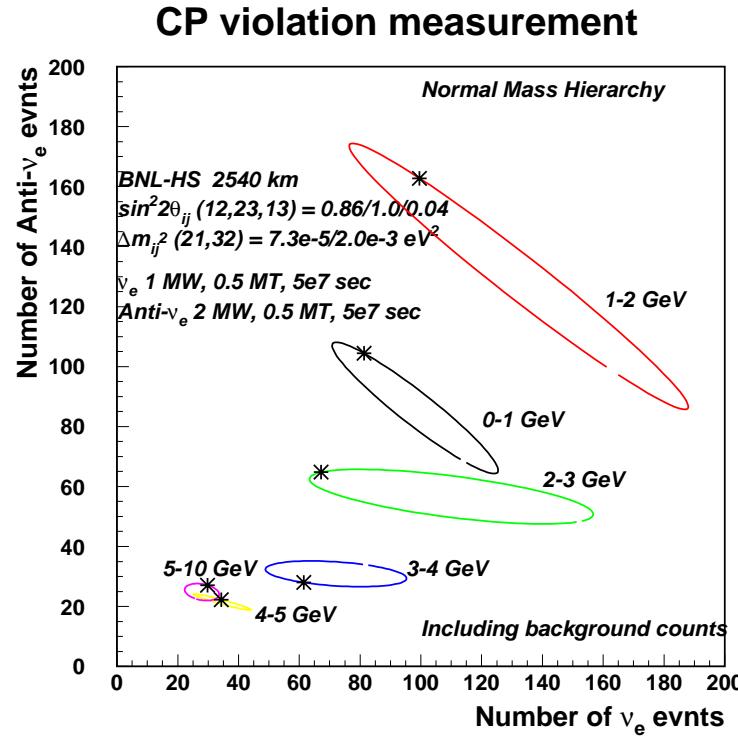
$$\Delta m_{21}^2 = 7.3 \times 10^{-5} eV^2, \Delta m_{31}^2 = 2 \times 10^{-3} eV^2$$

$$\sin^2 2\theta_{12} = 0.86, \sin^2 2\theta_{23} = 1.0$$

Very long baselines with a superbeam

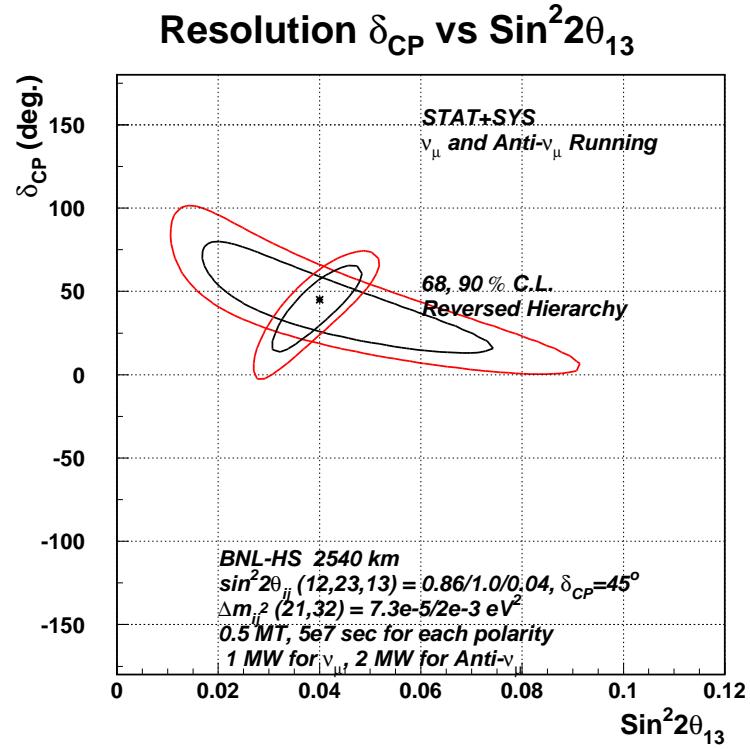
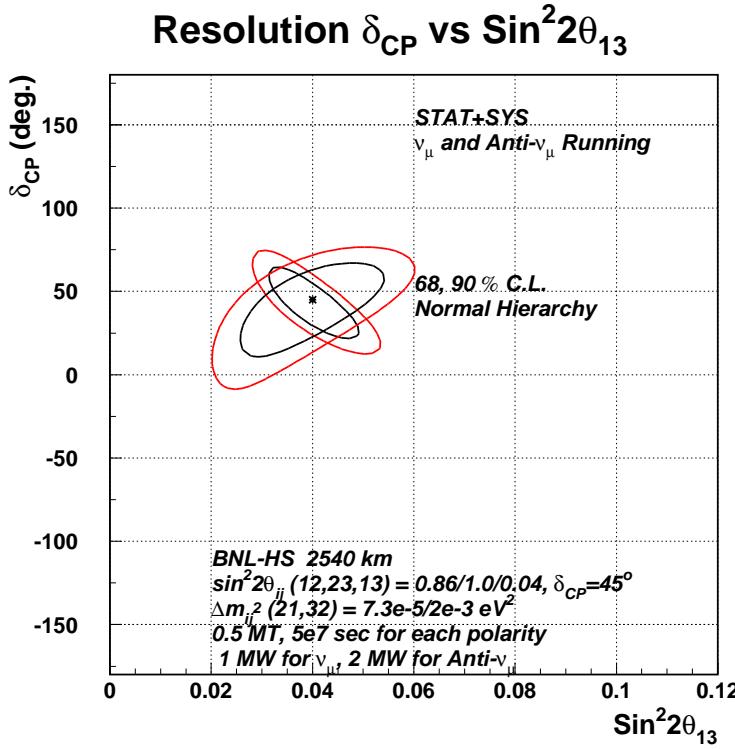
Combining Neutrino and Antineutrino

Very long baselines with a superbeam



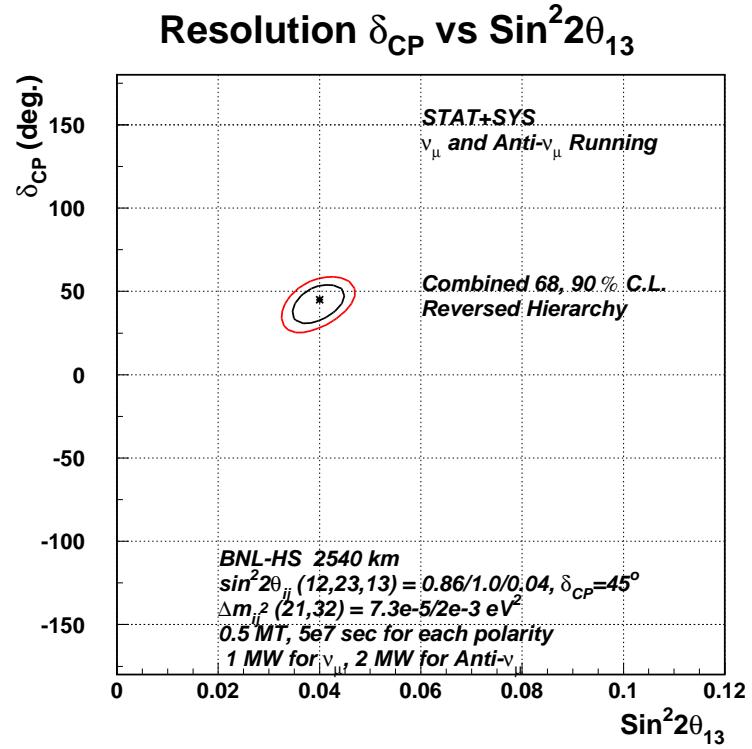
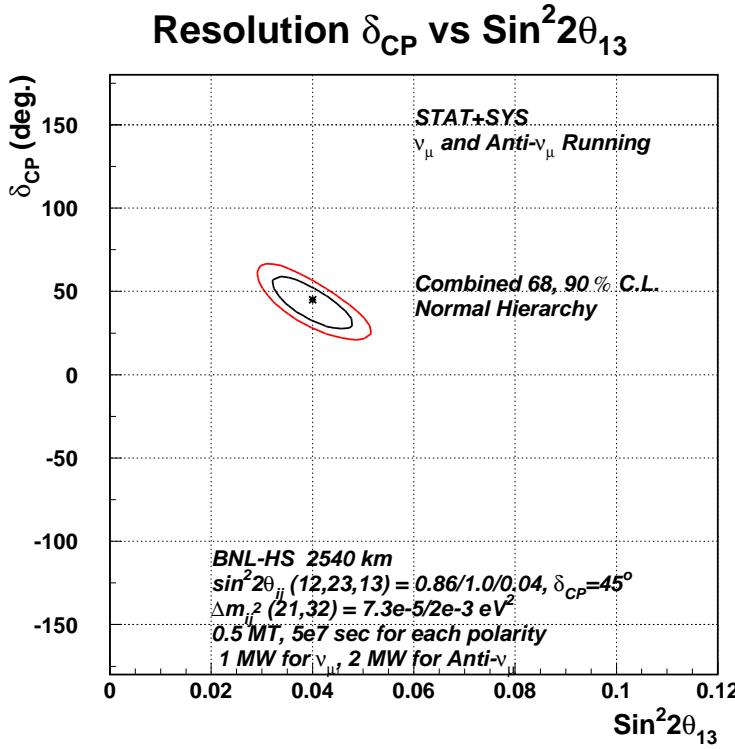
Note: No experiment can avoid matter effect. Explicit demonstration of CP violation must rely on a detailed fit to both neutrino and anti-neutrino data.

CP with Neutrino and Antineutrino



Very long baselines with a superbeam

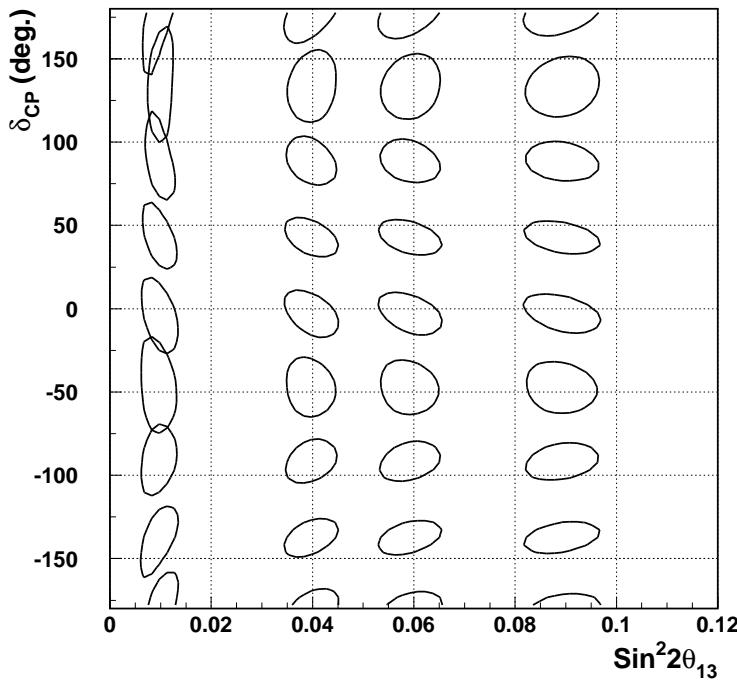
CP with Neutrino and Antineutrino



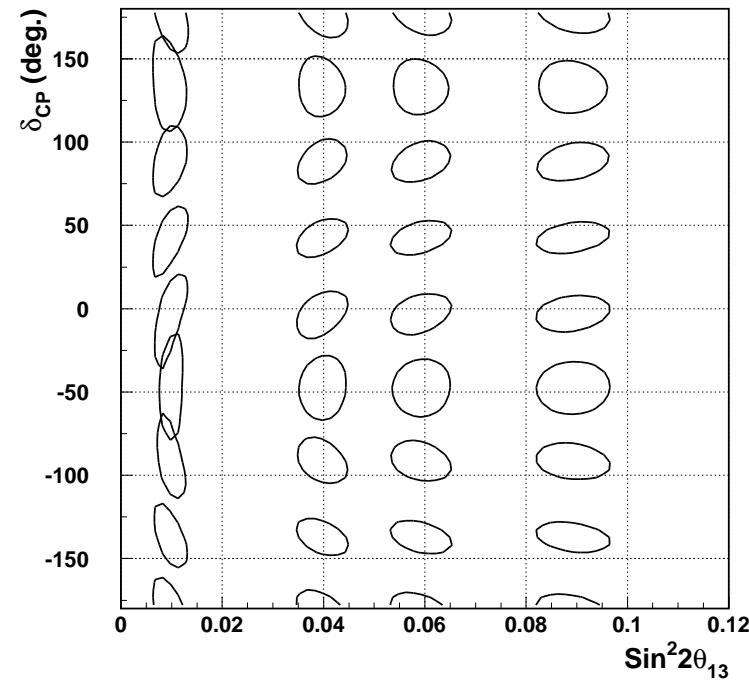
Very long baselines with a superbeam

CP with Neutrino and Antineutrino

Regular hierarchy νν and Antivνν running

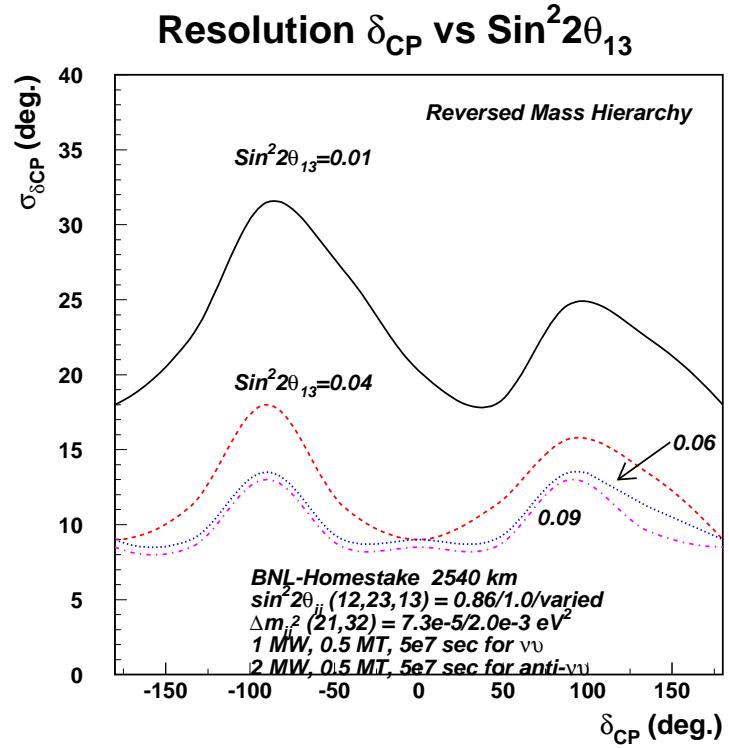
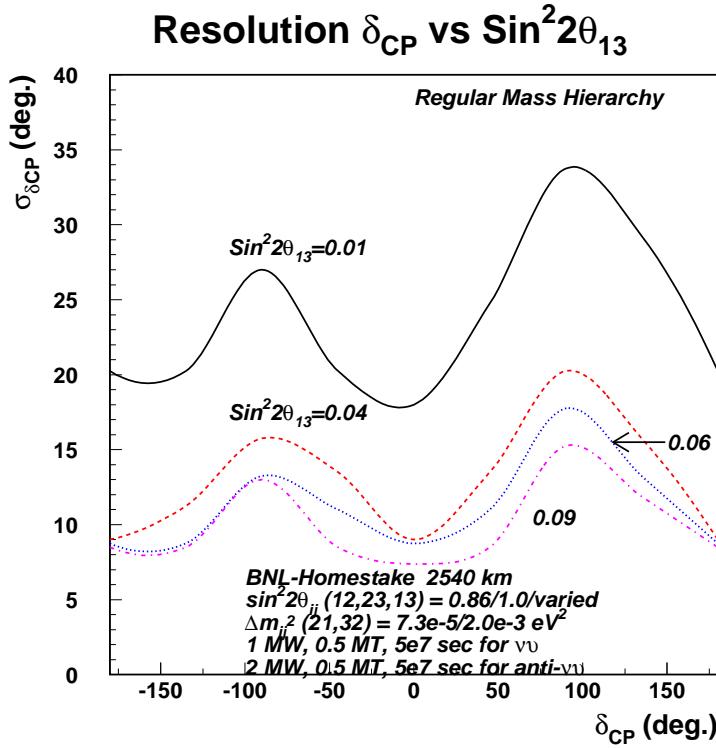


Reversed hierarchy νν and Antivνν running



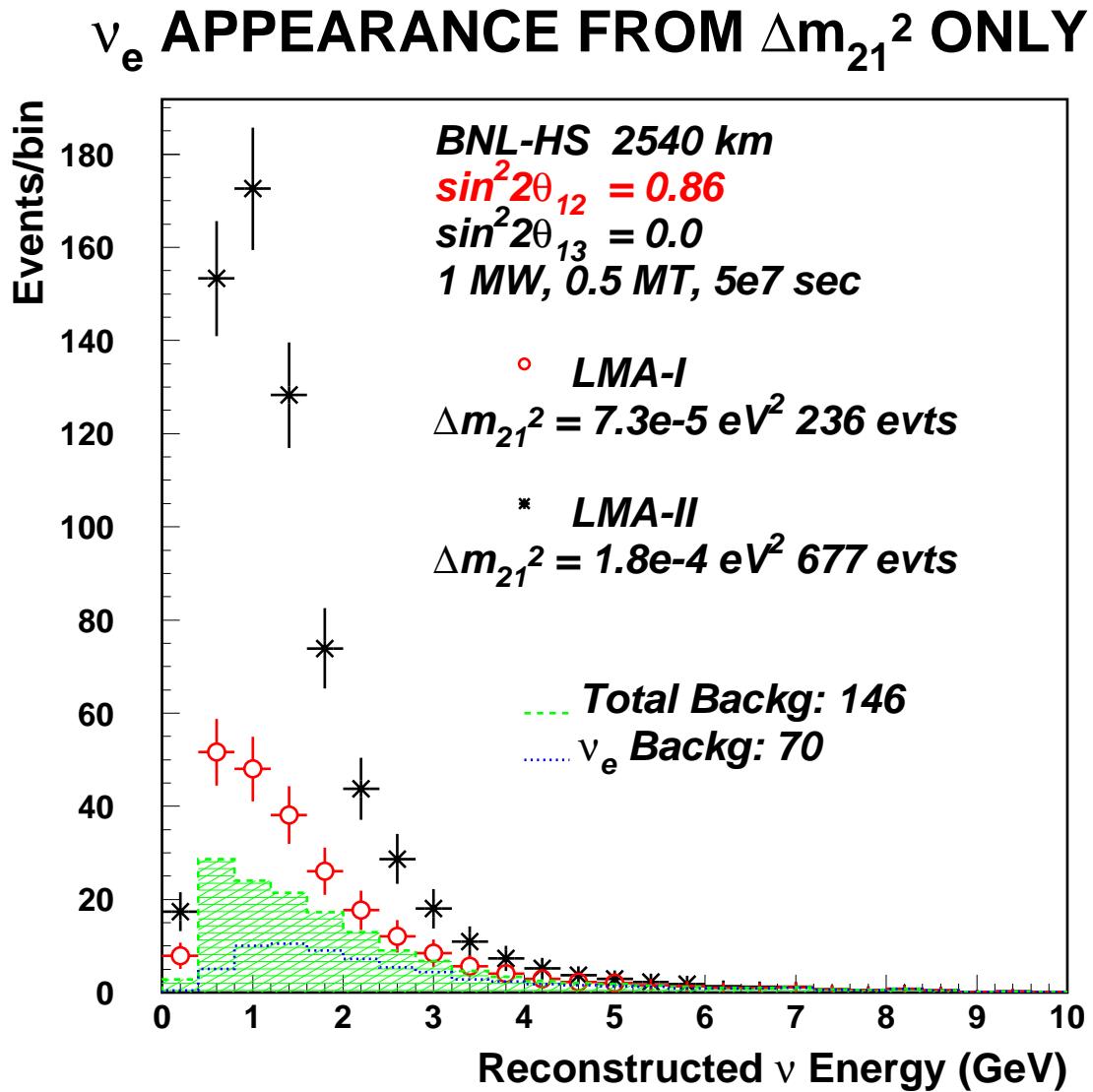
Very long baselines with a superbeam

CP with Neutrino and Antineutrino



Very long baselines with a superbeam

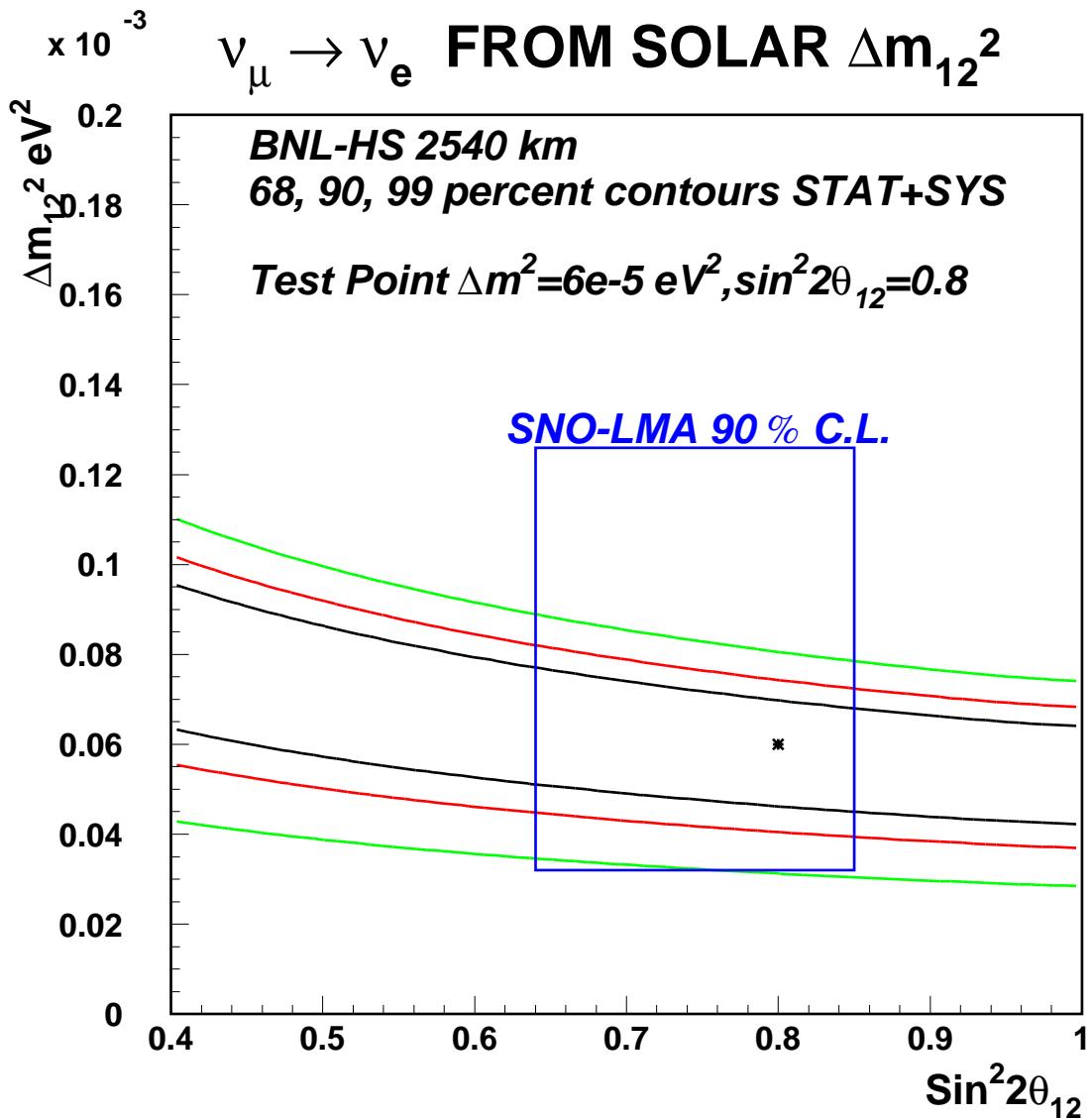
Measurement of Δm_{12}^2



$$\theta_{13} = 0, \Delta m_{12}^2 = 7.3 \times 10^{-5} \text{ eV}^2$$

Excess of ~ 90 events. Must know background

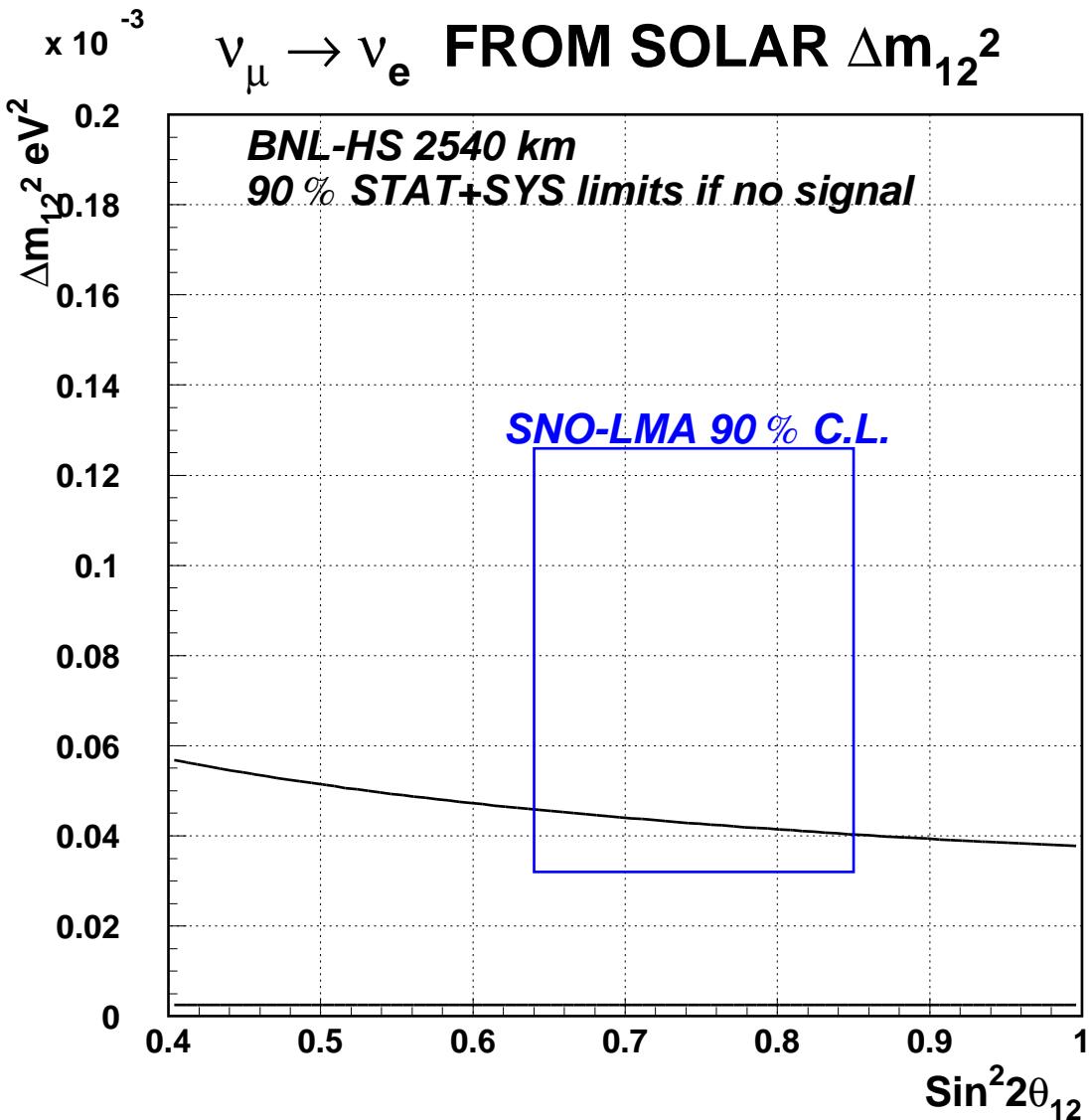
Measurement of Δm_{21}^2



Independent $\sim 15\%$ measurement of Δm_{21}^2

Needs $\sim 10\%$ error on backg. \Rightarrow near detector.

Limit on Δm_{21}^2 vs $\sin^2 2\theta_{12}$



If no signal then a limit can be obtained that almost eliminates LMA.

Analysis Flow Chart

How the experiment will proceed:

- After 2 years of running get a very precise measurement of Δm_{32}^2 from disappearance and definitive signal of oscillations.
- From the measured Δm_{32}^2 predict the shape of the electron spectrum including matter effects.
- Do we have a peak in the electron spectrum at the expected energy ? Yes No
- NO: Either $\sin^2 2\theta_{13}$ too small or inverted mass hierarchy $\Delta m_{32}^2 < 0$.
 - Get an independent measurement of Δm_{21}^2 at about $\pm 15\%$.
 - Run with anti-neutrinos. (next next slide)
- YES: GREAT NEWS ! GOTO NEXT SLIDE.

- YES: There is a peak in the electron spectrum from the neutrino beam.
 - Use Δm_{21}^2 from SNO and KamLAND and make a fit to the spectrum for CP angle versus $\sin^2 2\theta_{13}$.
 - Accumulate more statistics and make a combined fit for Δm_{21}^2 , δ_{CP} and θ_{13} .
 - Is the CP angle too small ? NO YES
- NO: Finished ! Still run antineutrinos for more precise δ_{CP} .
- YES: Run anti-neutrinos for more sensitivity on δ_{CP} .

Measure both $\sin^2 2\theta_{13}$ and δ_{CP}

- Running with anti-neutrinos if no peak in the electron spectrum from neutrinos

Is there a peak in the electron spectrum from anti-neutrinos ? **Yes No**

- **Yes** The mass hierarchy is inverted.
Proceed to measure $\sin^2 2\theta_{13}$ and CP angle with anti-neutrinos.
- **No** $\sin^2 2\theta_{13}$ is too small. Proceed to social work.

If inverted hierarchy;

measure both $\sin^2 2\theta_{13}$ and

δ_{CP} .

OR $\sin^2 2\theta_{13}$ is just too small for conventional beam.

Summary of our study

- Baseline of > 2000 km with wide band conventional beams are the next step in accelerator neutrino physics.
- Extraordinary, large physical effects will be seen in such an experiment.
- Very good sensitivity to neutrino properties.
 - $< 1\%$ resolution on Δm_{32}^2
 - $< 1\%$ resolution on $\sin^2 2\theta_{23}$
 - Sensitivity to $\sin^2 2\theta_{13} \sim 0.005$ over a wide range of Δm_{32}^2
 - Sensitivity to CP parameter $\pm 25^\circ$ with neutrinos alone.
 - Sign of Δm_{32}^2 over a wide range.
 - Measurement of Δm_{21}^2 at $\pm 15\%$
- The electron spectrum has a lot of physics. It can be extracted using some outside information on parameter.

Measurement matrix

Neutrino running only; Running: 5×10^7 sec.

Baseline: 2540 km; beam: 1 MW at 28 GeV; detector: 500 kT

	Δm_{32}^2	$\sin^2 2\theta_{23}$	Δm_{21}^2	$\sin^2 2\theta_{13}$ 90 % C.L.	δ_{CP}
$\Delta m_{32}^2 > 0.001$ $\sin^2 2\theta_{13} > 0.01$	< 1%	$\sim 1\%$	$\pm 15\%$	± 0.01	$\pm 25^\circ$
$\Delta m_{32}^2 > 0.001$ $\sin^2 2\theta_{13} < 0.01$	< 1%	$\sim 1\%$	$\pm 15\%$	Limit < 0.005	No Measure.

Not complete story, but an impression. Assume $m_3 > m_2 > m_1$.

Need good energy calibration for Δm_{32}^2 ($\sim 100 MeV$ LINAC ?)

Need small error on backg. for Δm_{21}^2 and CP. (Near Detector)

Some comments on detector

- Detector studies have started. Need more manpower.
- Water Cherenkov
 - 50 kT SuperK is existence proof.
 - Background rejection ? need another $\times 3$ to 5 to reach level in this talk.
 - Additional imaging capability ?
- Liquid Argon TPC
 - 100 kT module never built.
 - Current size 300Ton.
 - Needs detailed simulations.
- Any other technology ?

What is Next ?

White paper: hep-ex/0211001

Short paper: hep-ph/0303081, published PRD68,
012002, 2003

Can we use events such as $\nu_e + N \rightarrow e^- + \pi^+ + N$?

Background determination with near det.

- The experiment is technically feasible.
Direct costs.

AGS upgrade, Hill, Proton transp., horns,
decay tunnel: $\sim \$150M$

This can be a staged program that starts
with \$90 M at the AGS and \$150 M at
Homestake for first critical results.

- The detector has applications far beyond
accelerator neutrinos. And should have a very
diverse and rich physics program.

Detector: \$300 M for 10% PMT coverage ?

If water Cherenkov cannot have the needed
performance then what ?

Very long baselines with a superbeam

Two possibilities

- 1) Increase AGS to 2 MW by going to 5 Hz operation
- 2) Make finer grain detector at 100 kT. Use all events.

Optimization of the detector and accelerator needs much more detailed simulation study.